

STUDIES ON THE STRUCTURE
OF
ATOMIC NUCLEI

In-beam
gamma-ray spectroscopy

LARS CARLÉN



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by

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FK, Gb

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Abstract: This thesis concerns the level structure of atomic nuclei, studied by <u>in-beam gamma-ray spectroscopy</u>. Deuteron and heavy ion beams from accelerators were used to produce the reactions $^{23}\text{Na}(d, p\gamma)^{24}\text{Na}$, $^{148-150}\text{Sm}(\alpha, xn)^{149}\text{Gd}$, $^{144, 146}\text{Nd}(^{12}\text{C}, xn)^{150}\text{Dy}$, $^{144}\text{Sm}(^{12}\text{C}, 3n)^{153}\text{Er}$ and $^{154}\text{Sm}(^{16}\text{O}, 4n)^{166}\text{Yb}$. The emitted γ-rays were studied in singles and coincidence experiments. Excitation energies and γ-ray branchings were determined for levels in ^{24}Na up to 4.2 MeV excitation energy. /Nucl. Phys. A210, (1973) 458/ The high-spin level structure of the nucleus ^{149}Gd was interpreted in terms of shell model multiplets. Two isomers were reported. /Z. Phys. A300 (1981) 133 / A search for high spin isomers in ^{150}Dy gave no evidence for delayed transitions with half-lives longer than 10 ns. /Physica Scripta 17(1978) 103 / The level scheme of ^{153}Er was constructed and the properties of the energy levels were discussed and compared with theoretical calculations. / Accepted for publication in Nucl. Phys. / In the nucleus ^{166}Yb, four weak side-bands were observed besides the yrast cascade, which was followed up to its 24^+ state. The ground-state band was identified to its 18 member. The S-band was established from its 12^+ member. /Physica Scripta 24 (1981) 324 / Much of the data reduction was made with CARATE, a package of <u>computer programs</u> for interactive analysis of one-dimensional spectra. /Cosmic and Subatomic Physics Report LUIP 8201, LUNFD6/(NFFK-7014)/(1982), University of Lund.	
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STUDIES ON THE STRUCTURE OF ATOMIC NUCLEI

In-beam gamma-ray spectroscopy

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The thesis consists of this summary and the following papers:

- I. Energy levels of ^{24}Na from
the $^{23}\text{Na}(d, p\gamma)^{24}\text{Na}$ reaction
Nucl. Phys. A210 (1973) 458
(In collaboration with P. Ekström and J. Tillman)
- II. CARATE - a program package for interactive
treatment of one-dimensional spectra -
Cosmic and Subatomic Physics Report LUIP 8201,
LUNFD6/(NFFK-7014)/(1982), University of Lund.
- III. High spin shell model excitations in ^{149}Gd
Z. Phys. A300 (1981) 133
(International collaboration)
- IV. Search for high-spin isomers in ^{150}Dy
Physica Scripta 17 (1978) 103
(In collaboration with M. Piiparinen, H. Ryde,
S. A. Hjorth, A. Johnson and Th. Lindblad)

- V. High spin states and yrast isomerism in ^{153}Er
Cosmic and Subatomic Physics Report LUIP 8109,
LUNFD6/(NFFK-7009)/(1981), University of Lund, and
accepted for publication in Nucl. Phys.
(In collaboration with S. Jönsson, J. Krumlinde,
J. Lyttkens, N. Roy, H. Ryde, S. Strömberg,
W. Waluś, G. B. Hagemann and B. Herskind)
- VI. High-spin band structure in ^{166}Yb
Physica Scripta 24 (1981) 324
(International collaboration)

1. INTRODUCTION

The nuclei studied in this thesis are all unstable with short half-lives. They have been produced by nuclear reactions when suitable, stable target nuclei have been bombarded by deuterons, alpha-particles, ^{12}C and ^{16}O ions, accelerated to 1 - 10 MeV/nucleon.

The lowest energy used, at the same time the maximum energy available at the Van de Graaff accelerator in Lund, was suitable for nuclear structure studies of low-lying states in ^{24}Na . The states were populated by the reaction $^{23}\text{Na}(d, p \gamma)^{24}\text{Na}$ where a neutron is stripped off the incoming deuteron and absorbed into a shell model orbital. The proton then continues with an energy, which depends not only on its direction of movement and bombardment energy, but also on the state that absorbed the neutron. By measuring the energy spectrum of the protons in a fix, well defined angle, it is thus possible to study the energy levels in the residual nucleus.

The total cross section for such direct reactions are normally considerably smaller than those of compound reactions, where the projectile is totally absorbed by the target nucleus. However, when the bombarding energy is smaller than the Coulomb barrier the relations may be different. Then the deuteron is polarized /Opp/ so that its neutron can interact strongly with a target nuclei and

enter a shell-model orbital, while the proton is repelled by the Coulomb force. When the neutron has entered a bound excited state, it is possible to perform proton-gamma coincidence experiments and study the gamma decay properties. The Q-value of the reaction studied here is 4.73 MeV, which made it possible to study levels up to 4.2 MeV even though bombarding energies below 3 MeV were used.

At higher bombarding energies, using alpha particles and heavy ions as projectile, compound nuclei are formed by fusion between the target nucleus and the bombarding particle. The compound nucleus is strongly excited and cools down through particle evaporation. For the reactions used here, neutron evaporation dominates, since proton emission is hindered by the Coulomb barrier. The maximum number of neutrons which can evaporate depends on the excitation energy. It is possible to optimize the relative yield of a specific number of evaporation neutrons by proper selection of the bombarding energy. Reactions with 3 - 8 evaporation neutrons have been studied in this work.

The scientific interest in heavy ion nuclear reactions is not only due to the amount of energy transferable to the compound system. Heavy ion reactions make it possible also to bring into the compound system so much angular momenta that the rapid rotation causes major changes in the nuclear structure.

Bohr and Mottelson /Boh/ proposed some time ago that one manifestation of spectral structure effects in nuclei with high spin values could be the occurrence of "yrast traps", i.e. long-lived, high-spin, isomeric states close to the yrast line. This line is defined as the lowest energy - highest spin level sequence. An island of high-spin isomers near $N=82$ was soon discovered by Pedersen et al. /Ped/. In a search for gamma-radiation of life-times longer than 10 ns, they found a strong clustering for $64 \leq Z \leq 71$ and $82 \leq N \leq 88$ of high-spin isomers with life-times from a few ns to several hundred ns. However, the detailed properties of these isomeric states were not known. It was then a challenge to try to localize them and study their structure.

2. SHORT PRESENTATIONS OF THE PAPERS

2.1. Paper I.

Excited states in ^{24}Na were studied by means of the $^{23}\text{Na}(\text{d}, \text{p} \gamma)^{24}\text{Na}$ reaction. Targets of NaBr, evaporated on thin silver backings, were bombarded with 2.5 and 2.8 MeV deuterons. Excitation energies and gamma-ray branchings for 24 levels up to 4.2 MeV were obtained. Two previously unpublished levels, at 3944 ± 2 and 4195 ± 3 keV excitation energies, were found.

2.2. Paper II.

CARATE, described in paper II, is a package of computer programs for interactive data-reduction of one-dimensional spectra. It offers a "skeleton" framework for easy implementations of a wide-range of applications. It has a menu of commands for table of contents and selection of spectrum from a data input file, graphic display of a region of interest in the spectrum, calibration of the channel axis and other basic operations. Commands for special purposes may be included in the application parts, provided by the programming user.

A CARATE program is run from a standard graphic display terminal. The top lines of the screen are used for the standard command menu together with alpha-numeric information about the spectrum or spectra being treated. Space is also reserved for the special menu of the actual CARATE application. Below to the right, a graphics display is available and to the left there is a field for command/question/answer dialogue between the user and the program.

Paper II also describes some widely used applications. A general-purpose program for data manipulations such as summing spectra and background subtraction is first presented. Calculation of peak positions and areas is the standard spectrum analysis. Three different fitting programs, written elsewhere, have so far been slotted into CARATE.

FORTRAN77 (with very few exceptions) is used and programming details are given to make new implementations easy.

2.3. Paper III

High spin states in ^{149}Gd , populated in (α, xn) reactions, were investigated by in-beam gamma-ray and conversion electron spectroscopy.

Detailed gamma-ray excitation functions were measured for the $(\alpha, 4n)$ reaction using five bombarding energies between 42 and 53 MeV. Gamma-ray angular distributions were measured in two independent experiments with $(\alpha, 4n)$ and $(\alpha, 5n)$ reactions. The two sets of data were in excellent agreement.

With two Ge(Li) detectors, a four-parameter $(E_1, E_2, t_{12}, t_{1RF})$ list-mode coincidence experiment using the $^{148}\text{Sm}(\alpha, 3n)$ reaction gave prompt coincidence spectra for construction of the level scheme. However, it did not reveal any isomers with $T_{1/2} \geq 10$ ns. To find shorter-lived isomers a three-parameter (E_1, t_{1RF}, t_{2RF}) timing coincidence experiment was performed with a 2 cm^2 Ge detector in coincidence with a $5 \times 7.5\text{ cm}^2$ NaI(Tl) scintillator detector. It was then possible to identify two isomers with the half-lives 6.0(5) and 1.6(6) ns, respectively.

These experimental results, supplemented by measurements of gamma-ray linear polarisations and conversion coefficients in certain crucial details, established the ^{149}Gd high spin energy spectrum up to about 4 MeV. It was interpreted in terms of the spherical shell model with three valence neutrons in the $f_{7/2}$, $h_{9/2}$ and $i_{13/2}$ orbitals outside the ^{146}Gd core.

2.4. Paper IV.

The nucleus ^{150}Dy is found in the middle of the region where isomeric states with life-times within a wide time range from a few ns as have been observed /Ped/. This nucleus has two protons outside the essentially inert $Z=64$ core and two neutrons outside the closed shell, $N=82$ core. These four particles may form states with spin-values ranging from zero to 22 which is the highest spin that may be obtained from the $(\nu i_{13/2})^2(\pi h_{11/2})^2$ configuration. The residual interaction in this configuration may force the $I\pi=22^+$ level below other members of this configuration such as the 21^+ and 20^+ -states. The decay of such a 22^+ may then possibly proceed by an M2 transition to the 20^- level of configuration $(\nu i_{13/2} \nu f_{7/2})(\pi h_{11/2})^2$. This situation would then form an yrast trap with a measurable half-life.

Paper IV of this thesis reports on an experimental search for high spin isomers in ^{150}Dy . Thin foils of ^{144}Nd and ^{146}Nd were bombarded with ^{12}C beams from the 225 cm-cyclotron in Stockholm. Excited states in the residual nucleus ^{150}Dy were then reached in $(^{12}\text{C}, 6n)$ and $(^{12}\text{C}, 8n)$ reactions, respectively. Gamma-ray spectra, singles as well as correlated in time with respect to the cyclotron frequency, was made using a $\text{Ge(Li)}-\text{NaI(Tl)}$ Compton suppression arrangement. No evidence was found for delayed transitions with half-lives longer than about 10 ns.

The non-isomerism was explained, assuming states with spin 22 being populated in the reaction, by the fact that the 21^- level of the $(\nu i_{13/2} \nu h_{9/2})(\pi h_{11/2})^2$ configuration is forced down below the 22^+ level due to the strong $i_{13/2} - h_{9/2}$ interaction. This means that the decay now can take place by means of a fast E1 transition.

A two-dimensional gamma-gamma-coincidence experiment was performed using the Compton suppression gamma-ray spectrometer and an additional Ge(Li) detector. The most remarkable property of the coincidence spectra was the unusually large number of transitions of roughly the same strength observed in each spectrum.

2.5. Paper V.

In the systematic search /Ped/ for delayed cascades of gamma-ray with high multiplicity, isomeric states with half-lives of the order of 100 ns were found in light Er isotopes. However, the detailed decay pattern of the isomers observed was not known. Paper VI reports on an extensive study of high-spin states and yrast isomerism in ^{153}Er .

No transitions were known in this nucleus when the investigation started. Isotopically enriched ^{144}Sm targets were bombarded with 53-65 MeV ^{12}C ions from the FN Tandem Accelerator at the Niels Bohr Institute. With these beam energies two and three neutrons are evaporated from the

compound nucleus ^{156}Er . The assignment of gamma-rays to the product nuclei ^{154}Er and ^{153}Er , respectively, were based on a sum-spectrometer $/Tj\phi/$ measurement and conventional studies of excitation functions.

The average multiplicities of strong transitions were studied as a function of the bombarding energy using one $\text{Ge}(\text{Li})$ detector and nine $\text{NaI}(\text{Tl})$ counters, as described in reference $/\text{And}/$.

A search for delayed gamma-rays and precursors was made by chopping the beam and applying conventional delayed coincidence techniques. One intrinsic Ge and one $\text{Ge}(\text{Li})$ detector for energy measurements were used together with two $\text{NaI}(\text{Tl})$ crystals for timing requirements.

The gamma-ray spectrum from ^{153}Er was dominated by a cascade of five transitions. Their average multiplicities varied between 7 and 8 for all these transitions with the exception of the weakest one, at 712.0 keV, which had an average value of about 5 and a more narrow distribution. All five were found to have a strong delayed component with a common half-life of 373 ± 9 ns. The 712.0 keV transition had no prompt component in its time distribution. In conclusion an yrast cascade were observed, depopulating a high-spin isomer.

In order to establish the multipolarity, angular distributions of the singles gamma-rays were measured independently with two $\text{Ge}(\text{Li})$ detectors, one being

surrounded by a Compton suppression shield.

The angular distribution of the 712.0 keV gamma-ray was found to be isotropic, which would be expected for an isomeric transition. As the properties of this transition were crucial, a measurement of the conversion coefficients for the transitions in this energy range was performed. It was then concluded that the 712.0 keV transition is either of E3 or M1 character.

The results of gamma-gamma coincidence experiments are of decisive importance for the establishment of the level scheme. Two independent measurements were performed, at 63.0 and 65.0 MeV bombarding energy, respectively, using different detector arrangements. Both measurements gave the same results.

The results of the experiments described above formed the basis for the construction of the level scheme of ^{153}Er . The properties of the energy levels were compared with the results of calculations with a deformed shell model, and also with adjacent $N=85$ nuclides.

2.6. Paper VI

The conditions for significant population of high spin states are very favourable in the nucleus ^{166}Yb which is known to be one of the best rotors. Paper VI describes an investigation of high spin states in this nucleus,

populated in the reaction $^{154}\text{Sm}(^{16}\text{O},4\text{n})^{166}\text{Yb}$ at a beam energy of 80 MeV. Angular distribution measurements were performed with two spectrometers, one Ge(Li) detector at five angles between 58° and 148° , and another with a Ge(Li) detector in a Compton suppression set-up at five angles between 0° and 90° . Two independent sets of angular distribution coefficients were obtained.

Gamma-gamma-coincidence measurements were performed with an array of four Ge(Li) detectors and four NaI(Tl) detectors. About 300 million pairs of events were accumulated and the coincidence spectra were used for construction of the decay scheme.

Four weakly populated side-bands were observed besides the yrast cascade which was followed up to its 24^+ member. The ground state band was identified to its 18^+ state while the crossing super- or Stockholm band becomes its yrast band at 16^+ member. The S-band was established from its 12^+ state.

Theoretical calculations within the particle-rotor model gave level energies and transition rates in good agreement with the experimental results.

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To Professor Hans Ryde, my supervisor and friend, I wish to express my most sincere gratitude for his excellent guidance and encouraging support.

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I wish to thank all colleagues and friends for these years at the Department of Physics. Thank you all!

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3. REFERENCES

- And O.Andersson, R. Bauer, G.B. Hagemann,
B. Herskind and D.L. Hillis,
Phys. Lett. 72B (1978) 439
- Boh A. Bohr and B.R. Mottelson,
Physica Scripta 10A (1974) 13
- Opp J.R. Oppenheimer and M. Phillips,
Phys. Rev. 48 (1935) 500
- Ped J. Pedersen, B.B. Back, F.M. Bernthal,
S. Bjornholm, J. Borggreen, O.Christensen,
F. Folkmann, B. Herskind, T.L. Khoo,
M. Neiman, F. Puhlhofer and G. Sletten,
Phys. Rev. Lett. 39 (1977) 990
- Tjø P.O. Tjøm, I. Espe, G.B. Hagemann,
B. Herskind and D.L. Hillis,
Phys. Lett. 72B (1978) 439

ENERGY LEVELS OF ^{24}Na FROM THE $^{23}\text{Na}(\text{d}, \text{p}\gamma)^{24}\text{Na}$ REACTION

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Abstract: Excited states in ^{24}Na have been investigated by means of the $^{23}\text{Na}(\text{d}, \text{p}\gamma)^{24}\text{Na}$ reaction at incident deuteron energies of 2.5 and 2.8 MeV. Excitation energies and γ -ray decay for levels up to 4.2 MeV have been determined from proton-gamma coincidence spectra obtained with a surface barrier detector and a Ge(Li) detector on-line with a computer. Two new levels at 3944 ± 2 and 4195 ± 3 keV excitation energies are reported.

E NUCLEAR REACTIONS $^{23}\text{Na}(\text{d}, \text{p}\gamma)$, $E = 2.5$ and 2.8 MeV; measured $\sigma(E_p, E_\gamma)$. ^{24}Na deduced levels, E_x , branching ratios. Natural target.

1. Introduction

The nucleus ^{24}Na is a deformed doubly odd nucleus. The rotational model has had considerable success in describing the properties of the nuclei of mass number $A \approx 25$. In this model ^{24}Na is described as a proton and a neutron moving in a prolate deformed potential created by the remaining core nucleons.

The odd proton in ^{23}Na occupies the 7th Nilsson orbital with $\Omega_p = \frac{3}{2}$. The neutron captured in the (d, p) reaction will occupy any vacant orbital with its component of angular momentum equal to Ω_n . Two intrinsic states can be constructed from each Ω_n , one with $J = \Omega_p + \Omega_n$ and one with $J = |\Omega_p - \Omega_n|$. Some of the low-lying states of ^{24}Na have been interpreted in terms of such intrinsic states and rotational states built on these ^{1,2}).

The level structure of ^{24}Na has been studied by Sperduto and Buechner ³) by means of the $^{23}\text{Na}(\text{d}, \text{p})^{24}\text{Na}$ reaction. They analysed proton groups at 90° relative to the deuteron beam with a magnetic spectrograph, and obtained excitation energies of 19 levels in the residual nucleus. The same reaction was investigated by Daum ⁴) who obtained I_n values of some states from the angular distribution of the protons. The (d, τ) reaction on ^{25}Mg was used by Krämer *et al.* ²) to determine I_p values for transitions to some states in ^{24}Na .

The β^- decay of ^{24}Ne to ^{24}Na has been studied by Dropesky and Schardt ⁵), McDonald *et al.* ⁶) and by Asano *et al.* ⁷). Gamma-ray decay of excited states has been investigated by Greenwood ⁸) and Nichol *et al.* ⁹) by means of the thermal-neutron capture reaction. From Greenwood's measurements a level scheme of ^{24}Na with accurate excitation energies has been constructed ⁸), but this scheme is not complete because not all states are populated in the (n, γ) reaction.

Particle- γ -ray correlations from the $^{26}\text{Mg}(d, \alpha\gamma)^{24}\text{Na}$ reaction have been studied by Keverling Buisman *et al.*¹⁰). They measured branching ratios of the γ -ray decay of the levels up to 3.4 MeV with a NaI(Tl) scintillation detector, and from the angular correlation they inferred restrictions of spin and parity of several levels.

The $^{23}\text{Na}(d, p\gamma)^{24}\text{Na}$ reaction has been investigated previously by Becker *et al.* [refs.^{11, 12})], but they have so far published only preliminary results¹¹). The purpose of the present investigation with this reaction was to determine accurate excitation energies and γ -ray branchings of excited states in ^{24}Na .

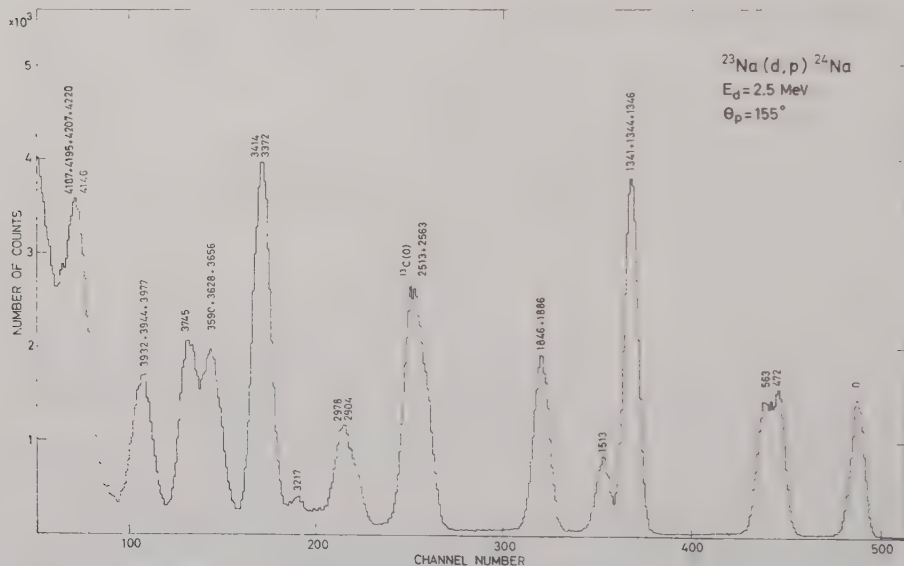


Fig. 1. Singles particle spectrum resulting from the $^{23}\text{Na}(d, p)^{24}\text{Na}$ reaction at $E_d = 2.5 \text{ MeV}$. The corresponding excitation energies (in keV) in ^{24}Na are indicated. The peak labeled $^{13}\text{C}(0)$ results from the ground-state proton group in the $^{12}\text{C}(d, p)^{13}\text{C}$ reaction.

2. Experimental procedure and results

2.1. EXCITATION ENERGIES

Excitation energies of the ^{24}Na levels were determined from a $^{23}\text{Na}(d, p\gamma)^{24}\text{Na}$ experiment with 2.5 MeV deuterons from the University of Lund 3 MeV Van de Graaff accelerator.

The beam had an intensity of 40 nA. The targets consisted of 100–300 $\mu\text{g}/\text{cm}^2$ NaBr evaporated on thin silver backings. It was checked by performing an experiment at the same deuteron energy with a CdBr_2 target that the bromine in the targets gave a negligibly small yield of protons and γ -rays.

Gamma-rays were detected with a true coaxial 43 cm^3 ORTEC Ge(Li) detector giving an energy resolution during the experiment of 8 keV FWHM at 2.0 MeV.

The γ -ray detector was positioned at 90° relative to the beam in the horizontal plane. Protons were detected with an ORTEC 150 mm², 1500 μ m depletion depth Si surface barrier detector mounted at 155° in the vertical plane through the beam. With this detector arrangement the γ -ray lines exhibited no Doppler shift. Elastically scattered deuterons were stopped in an 11 mg/cm² thick aluminium foil placed in front of the Si detector. A singles particle spectrum is shown in fig. 1.

The data from the experiment were processed by a standard two-parameter fast-slow coincidence system and were stored event by event on magnetic tape, for later sorting and analysis. The analysis was carried out with the aid of computer programs for peak finding and peak fitting.

TABLE I
Comparison of excitation energies (keV) of low-lying states in ^{24}Na

Present work	Ref. ¹³⁾	Present work	Ref. ¹³⁾
472.3 $\pm$ 0.2	472.31 $\pm$ 0.15	3413.6 $\pm$ 0.5	3409 $\pm$ 8
563.3 $\pm$ 0.2	563.31 $\pm$ 0.15	3590 $\pm$ 2	3589.1 $\pm$ 0.3
1341.3 $\pm$ 0.3	1341.36 $\pm$ 0.20	3627.8 $\pm$ 0.5	3623 $\pm$ 9
1344.4 $\pm$ 0.3	a)	3656.0 $\pm$ 1.0	3648 $\pm$ 9
1346.3 $\pm$ 0.3	1346.70 $\pm$ 0.25	3745.3 $\pm$ 1.0	3738 $\pm$ 8
1512.6 $\pm$ 0.3	b)		3850 $\pm$ 8
1846.1 $\pm$ 0.3	1846.1 $\pm$ 0.3		3899 $\pm$ 8
1885.5 $\pm$ 0.3	1885.4 $\pm$ 0.3	3932 $\pm$ 2	3929 $\pm$ 8
	2464 $\pm$ 8	3944 $\pm$ 2	
2513.3 $\pm$ 0.3	2512 $\pm$ 5	3977 $\pm$ 3	3977.2 $\pm$ 0.3
2563.3 $\pm$ 0.5	2561 $\pm$ 8	4146 $\pm$ 2	4140 $\pm$ 20
2904.1 $\pm$ 1.0	c)		4160 $\pm$ 20
2978.2 $\pm$ 0.5	2977.6 $\pm$ 0.3	4187 $\pm$ 2	4184 $\pm$ 8
3217.3 $\pm$ 0.5	3219 $\pm$ 5	4195 $\pm$ 3	
3371.9 $\pm$ 0.5	3371.7 $\pm$ 0.3	4207.0 $\pm$ 0.5	4206.8 $\pm$ 0.3
		4220 $\pm$ 3	4219 $\pm$ 8

a) 1344 $\pm$ 2 keV from ref. ¹¹⁾.

b) 1511 $\pm$ 2 keV from ref. ¹¹⁾.

c) 2911 $\pm$ 12 keV from ref. ²⁾, 2905 $\pm$ 15 keV from ref. ¹⁰⁾.

Some well established transitions in ^{24}Na were used for energy calibration. The energies of these transitions have been accurately measured by Greenwood in an (n, γ) experiment ⁸⁾. A second-order polynomial was fitted to these calibration points with a least-squares method. The transition energies were corrected for the recoil of the ^{24}Na nuclei.

Whenever possible the adopted excitation energies are averages from different cascade sums, each separate component being weighted by the intensity of that branch. The uncertainties have been estimated from peak location and calibration accuracy. The decay of the 0.47 MeV level was not observed in the coincident spectrum, because this level has a half-life of 20 ms, which is long compared to the time-window, but the transition energy was determined from a singles spectrum.

In table 1 the excitation energies from the present work are compared to those adopted by Endt and Van der Leun¹³⁾ and to some more recent works^{2, 10, 11)}. The energies in the compilation¹³⁾ are mostly due to Sperduto and Buechner³⁾ (those with 8–9 keV uncertainties) and to Greenwood⁸⁾. It can be seen that the results of the present investigation are consistent with the previously published data. In many cases the uncertainties in the present work are considerably smaller than in those published before.

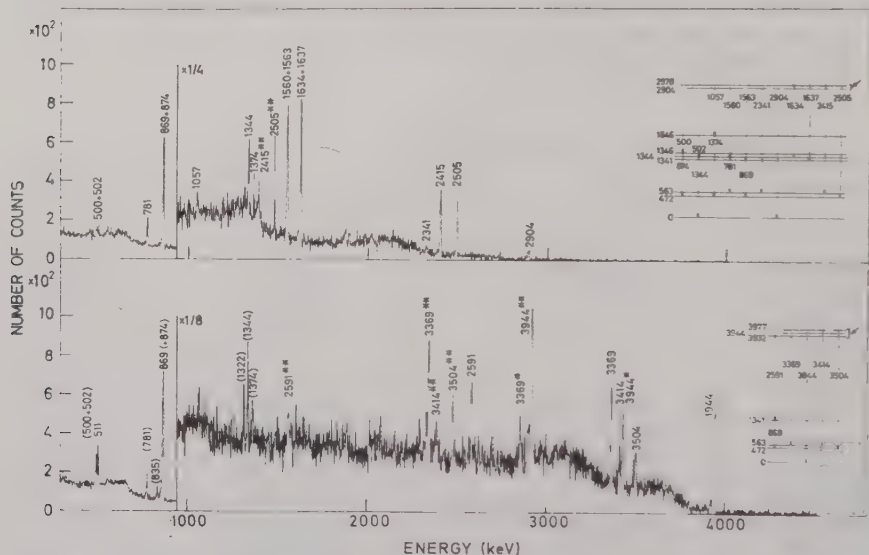


Fig. 2. Typical γ -ray spectra at 55° observed in coincidence with proton groups corresponding to the levels indicated by the arrows in the inserts. Transitions enclosed in parentheses are due to tails of other proton groups. The 511 keV peak is due to electron annihilation. Peaks marked with one and two asterisks are single and double escape peaks, respectively.

2.2. BRANCHING RATIOS

Branching ratios were determined from a $^{23}\text{Na}(d, p\gamma)^{24}\text{Na}$ experiment performed with 2.8 MeV deuterons from the 6 MV tandem Van de Graaff accelerator at Utrecht.

Gamma-rays were detected at 55° with a true coaxial 36 cm³ Philips Ge(Li) detector giving an energy resolution during the experiment of 5 keV FWHM at 2.0 MeV. The target-detector distance was 6 cm. The efficiency of the detector was obtained with calibrated radioactive sources placed in the target position. Protons were detected between the angles 166° and 174° with a Philips 200 mm², 1600 μm depletion depth annular Si surface barrier detector. Elastically scattered deuterons were stopped in a 50 μm thick mylar foil in front of the Si detector. The data were stored on magnetic tape with a three-parameter on-line system. The time spectrum

was a Gaussian with a FWHM of 6 ns and a true-to-random coincidence ratio of 10 : 1.

The experimental set-up corresponds to what Litherland and Ferguson call "Method II" ¹⁴), and ensures symmetrical population of the magnetic substates. This ensures that the branching ratios measured at 55° are correct as long as quadrupole radiation can be neglected.

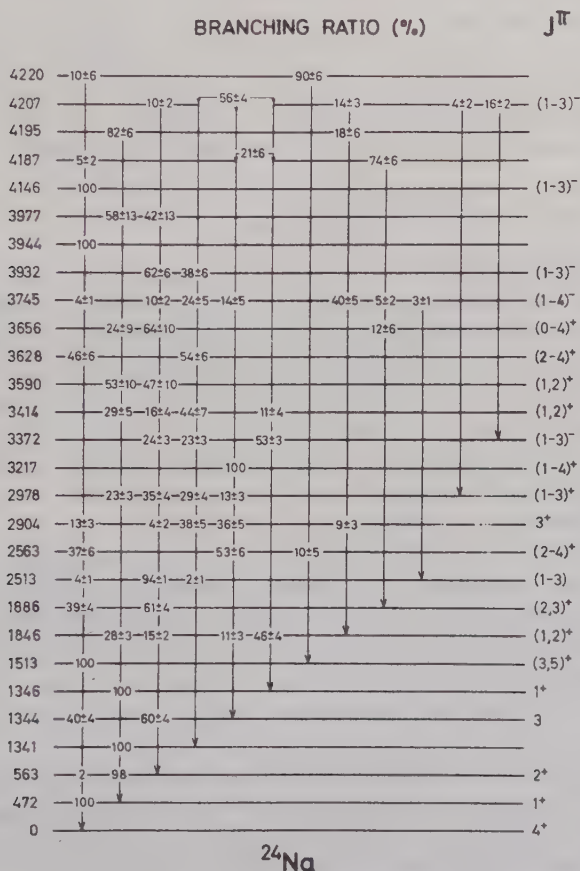


Fig. 3. Summary of the branching ratios from the present investigation. The branching ratio of the 0.56 MeV level has been taken from ref. ¹³), because the 91 keV transition was not observed in the present experiment. The J^π assignments were taken from refs. ^{2, 10, 13}).

In the spectra there are several composite peaks due for example to transitions from certain levels to levels within the 1.34 MeV triplet. It was not always possible to resolve these with sufficient accuracy. In these cases the intensities of the decay of the daughter levels were used for determining the branching of the parent level.

In those cases where the primary transitions were well resolved and the branchings could be calculated directly, the subsequent decay yielded intensities within the uncertainties. Whenever possible and necessary the transition intensities were corrected for the contribution from neighbouring proton groups and from the tails of other proton peaks.

The proton spectrum obtained was similar to that measured at $\theta_p = 155^\circ$, see fig. 1. Fig. 2 shows the γ -ray spectra coincident with two of the proton groups, with random coincidences subtracted.

The branching ratios measured are summarized in fig. 3. This figure also contains the J^π assignments of the levels as inferred from earlier experiments, assuming no octupole transitions to be present. The errors in the branching ratios were calculated from the statistical uncertainty of the peak areas plus a 5% uncertainty in the detector efficiency curve.

3. Discussion

There has in the past been some doubt about the existence of the 2.46 MeV level originally proposed by Sperduto and Buechner³), and the present investigation adds no proof for its existence. Nor has any trace been found of the levels at 3.85, 3.90 and 4.16 MeV (table 1). On the other hand two hitherto unreported levels at 3944 ± 2 keV and 4195 ± 3 keV are found. The support for the 3.94 MeV level is a strong 3.94 MeV ground-state transition and the fact that this transition is coincident with protons corresponding to an excitation energy of 3.94 ± 0.02 MeV in the ^{24}Na nucleus. The support for the 4.195 MeV level is a 3.72 MeV transition to the 0.47 MeV level and a 2.35 MeV transition to the 1.85 MeV level.

The branching ratios measured in the present work are generally in good agreement with those measured by Keverling Buisman *et al.*¹⁰). In the decay of the 1.85 MeV level the transition to the 1.344 MeV level has been identified. This transition was tentatively assigned¹⁰). This is also the case for the ground-state transition from the 2.51 MeV level. According to the same authors the 2.90 MeV level decays partly to the 1.89 MeV level, but this transition was not observed in the present experiment.

In the course of this work the branching ratios were measured with the experimental set-up of subsect. 2.1, with the γ -ray detector at 125° . The branching ratios obtained in that run are generally in good agreement with those obtained as described in subsect. 2.2. For a few transitions, however, the ratio of the intensities of two transitions depopulating the same level disagree by more than a factor of 2 between the two runs. For instance the adopted decay (fig. 3) of the 2.56 MeV level is $37 \pm 6\%$ to the ground state and $53 \pm 6\%$ to the 1.344 MeV level, while the run with the γ -ray detector at 125° and the Si detector off axis gives $60 \pm 10\%$ and $25 \pm 5\%$ respectively. This shows that when measuring branching ratios at 55° or 125° in an experiment in which one detects also the outgoing particles it is very important that these are detected in a counter system which is symmetrical with respect to the beam.

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References

- 1) C. Daum, Nucl. Phys. **51** (1964) 244
- 2) E. Krämer, G. Mairle and G. Kaschl, Nucl. Phys. **A165** (1971) 353
- 3) A. Sperduto and W. W. Buechner, Phys. Rev. **88** (1952) 574
- 4) C. Daum, Nucl. Phys. **45** (1963) 273
- 5) B. J. Dropesky and A. W. Schardt, Phys. Rev. **102** (1956) 426
- 6) R. E. McDonald, J. A. Becker, A. D. W. Jones and A. R. Poletti, Phys. Rev. **181** (1969) 1631
- 7) Y. Asano, T. Hagiwara, K. Ebisawa and T. Murata, J. Phys. Soc. Jap. **25** (1968) 1727
- 8) G. A. Bartholomew *et al.*, Nucl. Data **A3** (1967) 402
- 9) L. W. Nichol, A. H. Colenbrander and T. J. Kennett, Can. J. Phys. **47** (1969) 953
- 10) A. S. Keverling Buisman, Ph. B. Smith, P. J. M. Smulders and H. Gruppelaar, Nucl. Phys. **A176** (1971) 161
- 11) J. A. Becker, R. E. McDonald and R. W. Nightingale, Bull. Am. Phys. Soc. **14** (1969) 1221
- 12) J. A. Becker, private communication
- 13) P. M. Endt and C. van der Leun, Nucl. Phys. **A105** (1967) 1
- 14) A. E. Litherland and A. J. Ferguson, Can. J. Phys. **39** (1961) 788

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CARATE

- A PROGRAM PACKAGE FOR INTERACTIVE TREATMENT
OF ONE-DIMENSIONAL SPECTRA -

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ABSTRACT

CARATE is a program package for interactive use of spectral analysis codes. This report describes its general outlines and how to run four different applications from a standard graphic display terminal connected to a medium-sized mini-computer. FORTRAN77 is used and programming details are given to facilitate new implementations.

1. INTRODUCTION

Computers have been used for the evaluation of spectral data for a long time and the wider utilization of multi-user, time-sharing computer systems has increased the use of interactive programs. Even for the most trivial treatment, such as the plotting of raw data as histograms, the interactive approach is found to be very convenient.

However, a fast and efficient dialogue between the user and the program requires a standardisation in dialogue syntax and command language. The present report concerns a package of computer programs for interactive communication between the user and the program for the analysis of one-dimensional spectra. Its main program is a "skeleton" framework into which user's application subprograms are easily slotted. The package consists of one general purpose part for table of content listings of input data, spectrum selection for treatment, display of histogram with a graphic terminal, limits for region of interest, etc. This part has a structure for simple implementations of new features as well as completely new applications. The other part is a set of applications for data manipulation and analysis using fitting programs written elsewhere.

In Section 2 the general structure of the programs is described. The special features of four different applications are presented in Section 3. The programming user, who is interested in making new implementations and therefore in knowing the codes, will find useful information in Section 4, which contains descriptions of the source programs: subroutines, variables and common blocks. Finally, Section 5 specifies hardware requirements. In the appendices hints are given for CARATE runs on the Lund University Computer for Advanced Science (LUCAS), together with short form command menus for the implemented applications.

2. GENERAL OUTLINES

A CARATE program is run in an interactive fashion by using a computer display terminal of Tektronix 4010 series or a compatible equivalent*). Such a terminal has a normal keyboard and a storage-type cathode-ray tube (CRT) for display of alpha-numeric characters. It is also possible to display graphic pictures by drawing vectors between any positions on the screen. Moreover, this series of terminals has a graphical input facility. A special command to the terminal makes it display a cross-hair

*)

E.g. video display terminals with a Tektronix compatible graphics option.

cursor. The cursor is movable by two thumb-wheels, one for the vertical line of the cross-hair, the other for the horizontal line*). When the cursor is displayed as the response of a selected command, the user should position it properly and then press one key on the keyboard. This causes the terminal to inform the program which key was pressed and give the coordinates of the cursor.

CAL CHA-ROI-GRA CUR DEF GET INDATE LIST LOG MARKER SAVE TAG QUIT WIPE
800807- 10 4096 CHNLS. TITLE: LARS READING SPECTRUM 23 FROM BUSTER

FIT:DEFAULT END LINEAR NUMERIC PEAK RETURN START WIPE YES

CHA
CHNL LEFT,RIGHT:
510,500

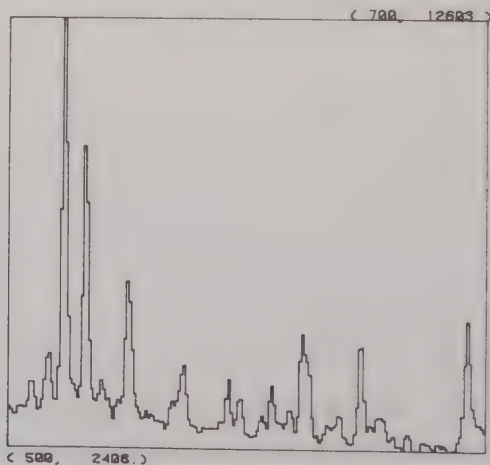


FIG. 1

In the layout of the display screen in CARATE programs, as illustrated in fig. 1, the top lines are used for the standard command menu together with alpha-numeric

*) On other types of terminals, the cursor can be moved around the screen under the control of special cursor movement keys.

information about the spectrum or spectra being treated. Space is also reserved for the special menu of the actual CARATE application. To the right, below these headlines, a graphic display area is available and to the left there is a field for command/question/answer dialogue between the user and the program. Since the terminal has a storage CRT and saves the display only on the screen, neither scrolling nor partial erasure are possible. When the dialogue area is used up, the user should request the program to wipe the screen, i.e. erasure and redisplay of headlines and graphics.

The user selects what is to be performed by typing a command on the keyboard, terminated by <RETURN>*). Although some commands for clarification may appear on the menu with several characters, only the first three have significance. The program then either performs the selected operation directly or asks for further information. In the case of numerical input, data are read as REAL numbers with free format for which the host computer specifications should be obeyed. Certain commands activate the cross-hair cursor, which should then be positioned properly before pressing the appropriate keyboard button.

*)-----

Throughout the text, the symbols "<" and ">" are used to define one key on the keyboard.

2.1. Start-up procedure

In order to get a proper set of suitable parameters for a session, a sequence of specifications is initiated at the start:

1. Main program: presentation and specification of terminal type.
2. Application routine: activities depend on the selected program.
3. Specifications of the region of interest and display of headlines and histogram.
4. Wait for command

2.2. Spectral data

The standard CARATE menu has a command for reading spectra from external mass memory. To execute this command successfully, the spectra must have been written properly. Programs for efficient read/write operations are very computer-dependent and therefore not described here. Appendix A presents some programs for writing and the detailed specifications are given on FORTRAN code level in Section 4. In addition to the channel data, each spectrum has its description block, presented in table 1 and specified in more detail in Section 4.

TABLE 1.

Contents of the spectrum description table

Basic spectrum identifier: date YYMMDD
 number NNN
Number of channels
Spectrum format code (depends on the computer system,
 see Appendix A)
Calibration of channel axis: degree of polynomial (1-3)
 polynomial coefficients
Normalisation factor
Reserved, format-dependent parameters
Free space for user's application
Spectrum title (< 80 characters)

The basic identification of a spectrum is made up by the identity date YYMMDD, which normally is its date of creation, and the identity number NNN with 1-3 digits. Each such identification YYMMDD-NNN should be kept unique. During a CARATE session, a default YYMMDD value may be defined, which as long as activated, causes the program to ask only for the number NNN for spectrum specification. Additional principles of identification are easily implemented within the application parts by the programming user.

2.3. CARATE standard commands

The command CALIBRATE will accept input of degree (1-3) and coefficients of a polynomial for the calibration of the channel axis. After calibration of the channel axis,

MARKER is useful to mark a specified channel equivalence within the region of interest.

The terminal screen is not large enough to display thousands of channels with sufficient resolution. Therefore the user may select a part of the current spectrum as a "region of interest" (r-o-i). CARATE has three modes for the specification of the limits of this region:

1. CHA: channel number limits
2. ROI: units of the calibration
3. GRA: graphical input of the limits

The third alternative is usable only for the selection of a part of the region already displayed, i.e. an expansion. Before drawing a histogram for the display of the region of interest, the minimum value of the region is subtracted. The vertical scale is automatically calculated to show the maximum value at the top. The scale is selectable linear or logarithmic.

Since a storage screen is used, a command WIPE is implemented for screen cleaning and re-display of the region of interest. DEFAULT will do the same but also reset parameters in the application program to their default values.

A table of contents for the input file is shown after the command LIST. This is done automatically when a spectrum is asked for which is not in the input file. Often certain spectra are wanted time after time. Up to nine such spectra may be given their own temporary tag numbers (1-9) for one CARATE session. A tag is allocated graphically after the command TAG which causes a display of the table of content for the input file and activates the cross-hair cursor. The user should then position its horizontal line across the title of the spectrum to be tagged and press one digit (1-9). The tagged spectra may afterwards be read from the input file just by pressing their tag digits. This feature is implemented in some of the applications descibed in Section 3. Exit from the tagging procedure is made by pressing any key other than 1-9.

To get information about a displayed channel, the cross-hair cursor is very convenient. It is activated by the command CURSOR. After positioning the vertical line of the cursor in a channel and pressing the "space" bar of the keyboard, the user will get the channel number, its calibrated equivalence and the number of counts in the specified channel. All keys other than the space bar will cause the program to turn off the cursor and wait for a 3-letter command.

A proper exit from CARATE and return to the monitor program is performed by the command QUIT.

2.4. Output of results

Besides the short-form outputs given directly to the user during the dialogue, there is often a need of a detailed logging of results, e.g. for documentation or further treatment in the computer. The CARATE main menu has a switch option for turning this output on or off.

3. APPLICATIONS

This section describes the use of four different applications slotted into CARATE for reduction of nuclear spectroscopy data at LUCAS. A general-purpose program MANIPU for data manipulations such as summing spectra and background subtraction is first presented. Calculations of peak positions and areas is the standard spectrum analysis. The advantages of simplicity and detailed documentation /Bev/ motivate the choice of SUSIE fitting routines as a second example of a CARATE application. However, more sophisticated codes are needed for stable final fitting values and fast analysis of complicated spectra. FIT-1 /Led/ fullfills these criterions, although its complexity leaves even the modest requirements on transparency and structure in the code unsatisfied. Up to 40 parameters are allowed to vary within one single fit which means that very complicated multiplets may be analysed. However, all peaks within the fitting interval

are considered to have the same shape parameters. The feature of individual peak widths within one fitting area is offered by GAUSS, the fourth application, which uses a least-squares method to fit a parabolic background and up to six skewed Gaussians to a part of a spectrum.

3.1. CARATE-MANIPU

MANIPU is a basic application program for data manipulations such as a shift along the channel axis, bunching channels together, smoothing, background subtraction and summing of spectra. The channel content is handled as integers within the range

$$-2147483649 < N < 2147483648.$$

The program has two data buffers and the data flow during the implemented operations is shown in fig. 2. A spectrum read directly to the output buffer will keep its description block until the channel content is modified in any way. Then a new spectrum is created, an identity number YYMMDD-NNN is assigned, the number of channels is updated and a new title is asked for. The identification date of an output spectrum is by default calculated from the date of the actual MANIPU session. It is, however, possible to override this by a date specified by the user issuing the command OUTDATE. The spectrum number NNN is set equal to one at start of session and is automatically

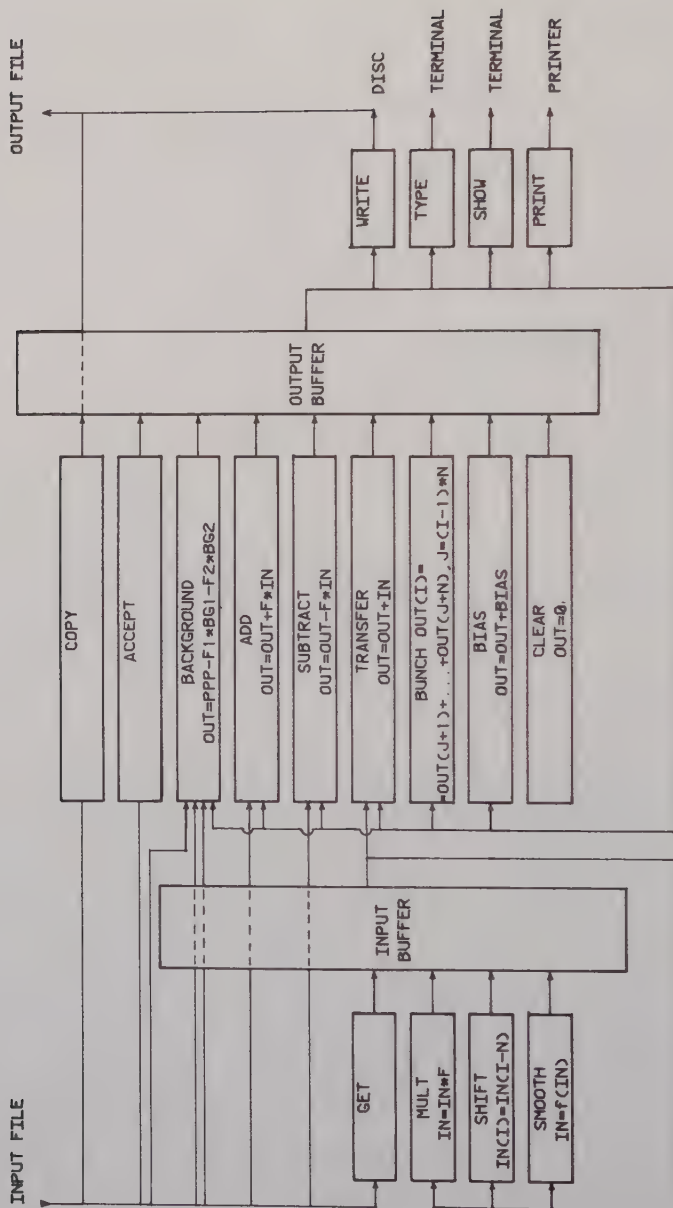


FIG. 2

increased by one each time a spectrum is created. The command NUMBER may be used to define NNN manually.

If no cost of computer and data transfer time were involved, each modification of the data could be shown graphically. However, this is not the case and the number of changes in the data is often very high. Therefore, in order to reduce operation time, the graphic display may be switched off by the command DISPLAY, which has an influence on certain commands.

During the initialization, the user must specify whether separate input and output files are wanted. If so, the copy option is made possible. Thereafter the program waits for commands. The MANIPU command menu is presented below and in short form in Appendix C.

ACCEPT

The program asks for a spectrum identification number and reads the spectrum directly into the output buffer.

ADD

The program asks for a spectrum identification number and reads the spectrum into the input buffer, then asks for a factor F and performs for every channel I:

$$OUT(I) = OUT(I) + F*IN(I)$$

BACKGROUND

In, for example, a coincidence experiment, some spectra have a background portion which must be reduced by subtracting weighted "background-spectra" to get the significant net spectrum. Since this often means repetition of a series of operations, a special command has been implemented. It is then assumed that all input spectra have the same id-date YYMMDD. The program starts with the assumption that the net output spectra will be bunched and asks for the number of channels N in each bunch. If $N \leq 0$, no bunching will be performed. The program asks for a bias B to be added to the net output spectrum (to avoid negative numbers). Finally it starts looping by asking for the id-number PPP of the spectrum to be background-subtracted, the id-number of the corresponding background spectrum BG1, its weighting factor FF1, another background spectrum BG2 and its factor FF2 and finally an alpha-numeric title for the output spectrum. This title will be added to a default title describing the output spectrum by stating its origin:

YYMMDD:PPP-FF1*BG1-FF2*BG2+B BUNCH: N

BIAS

If there is a spectrum in the output buffer, a bias value B will be asked for and added to the output buffer data for all channels I:

$$OUT(I) = OUT(I) + B$$

BUNCH

If there is a spectrum in the output buffer, the number of channels in each bunch will be asked for and the output buffer will be changed:

$$\text{OUT}(I) = \text{OUT}(J+1) + \dots + \text{OUT}(J+N) \quad J = (I-1)*N$$
$$\text{OUT}(I+N) = \dots\dots\dots$$

CLEAR

This command resets the output buffer (zero in all channels).

COPY

The program asks for a spectrum identifier, reads the spectrum to the output buffer and writes it directly to the output file.

DISPLAY ON/OFF

This command switches the updating of the graphic display on or off for certain commands.

INPUT

This command is used for reading data from the keyboard to a continuous series of channels in the output buffer. The program asks for the first channel number, where the new

data should be introduced and the number of channels to be read. It then reads the data from the keyboard directly to the output buffer.

MULTIPLY

The program asks for a factor F and performs for each channel I of the input buffer:

$$IN(I) = IN(I)*F$$

NUMBER

The program asks for the current number of next spectrum to be created in the output buffer.

OUTDATE

The program asks for the identity date YYMMDD of next spectrum to be created in the output buffer.

PRINT

With this command the spectrum in the output buffer may be printed on a line-printer.

SHIFT

Here the program asks for the number of channels N to shift and then performs for each channel in the input buffer the transform:

$$IN(I) = IN(I-N)$$

Arguments outside the spectrum limits are dismissed!

SHOW OUTPUT BUFFER

The region of interest of the output buffer will be shown.

SMOOTH

The following smoothing operation will be performed for all channels in the input buffer

$$IN(I) = 0.25*IN(I-1)+0.5*IN(I)+0.25*IN(I+1)$$

The two end channels are smoothed over only two channels, as if the next channel had the same contents.

SUBTRACT

A spectrum identifier and a factor F is asked for, the spectrum is read into the input buffer and then for each channel in the output buffer the operation is performed:

$$OUT(I) = OUT(I) - F*IN(I)$$

TRANSFER

The operation

$$OUT(I) = OUT(I) + IN(I)$$

is performed for all channels I.

WRITE

The output buffer spectrum is written on the output file.

3.2. CARATE-SUSIE

SUSIE, a general purpose program for the treatment of one-dimensional spectra, was written by M. Neiman /Nei/. Its peak-fitting part with the subroutine CURFIT, taken from ref. /Bev/, is implemented here. At start of a SUSIE session, the program asks for the name of an output save file and the peak full width at half maximum (FWHM), which is kept fix during the fit. This value may be changed later by the command <N>. By default, the fit region is equal to the region of interest. The command FIT will activate the cross-hair cursor and accept single-character commands.

Provided with start <S> and end <E> channels of the fit interval together with the initial values of the peak positions <P>, a linear background plus one to three Gaussian peaks (all of the same fix width) will be fitted to the data. The function used is

$$Y(x) = A_1 + A_2x + A_4e^{-\frac{1}{2}\left(\frac{x-A_5}{A_3}\right)^2} + A_6e^{-\frac{1}{2}\left(\frac{x-A_6}{A_3}\right)^2} + \dots$$

The number of peaks within the interval is specified by the number of initial hints of their positions. The

interval limits and the initial peak positions are shown graphically as response of the correponing commands.

Start values for the background are calculated from the interval limits. The command <L> will initialize a least squares fit using an algoritm of Marquardt /Mar/, which combines a gradient search with an analytical solution developed from linearisation of the fitting function. After the fit the function is shown grapically and the final coefficients A_i are used for calculation of the area and an estimation of the uncertainty in the area of each peak.

The single-letter command <Y> will send the final result to the output save file.

3.3. CARATE-FIT-1

In FIT1, written by M. Lederer /Led/, the least squares fitting is done by VARMIT /Dav/, which is an iterative gradient algoritm with variable metric. The peak shape is approximated by a Gaussian with leading and trailing tails:

$$\begin{aligned}
 y &= H \cdot e^{-\frac{(x-x_0)^2}{2\sigma^2}} & -T_l \leq x - x_0 \leq T_h \\
 &= H \cdot e^{\frac{T_l^2}{2\sigma^2}} \cdot e^{-\frac{T_l(x-x_0)}{\sigma^2}} & x - x_0 < -T_l \\
 &= H \cdot e^{\frac{T_h^2}{2\sigma^2}} \cdot e^{-\frac{T_h(x-x_0)}{\sigma^2}} & x - x_0 > T_h
 \end{aligned}$$

where H is the height of the peak at $x=x_0$ and $\sigma = \text{FWHM} / \sqrt{8 \ln 2}$.

The peak shape is thus specified by the full width at half maximum (FWHM) and the joining points of the lower and upper exponential tails relative to the peak position. All the peaks included in a fit are assumed to have the same shape parameters. These may either be included in the fit as free parameters or kept fixed, either given as input values by the user or calculated by the program from interpolation of stored standard peaks. A tail parameter greater than 200.0 will remove the corresponding exponential tail. The number of free parameters must not exceed 40.

When the shape parameters are allowed to vary, start values may be given by the operator. Otherwise the program will supply its own estimate. Default values of the tail parameters are 200.0, i.e. the tails are eliminated.

At the start of a FIT-1 session, the program asks for the names of the spectrum input file and two files for output of results, one for a short-form table and the other for line-printer plots of the accepted fittings.

The peak shape mode may be specified by the 3-letter commands VARIABLE and FIX. The command FIT will display the cross-hair cursor and accept single-character commands.

The start <S> and end <E> of the fitting interval should closely confine the peak(s). The number of peaks within the interval is given by the initial hints of their positions <P>. Fit interval limits and initial peak positions will be marked on the display.

Shape parameters may be specified numerically <N> and will then be treated as initial values for the fit (variable shape) or fixed parameters. A fit will be performed after the following background specifications:

<F> = Fix linear background through the endpoints of the fit interval.

<L> = Linear, fitted background.

<Q> = Quadratic, fitted background.

After a fit the function is shown graphically on the display and the FWHM and the tail parameters are given numerically together with a question whether the results are to be saved. <Y> will save the results on the table file and a line-printer plot on the plot file.

Well defined peaks, i.e. strong single peaks on linear backgrounds, may be used for shape calibration. By issuing the single-letter command <I> before fitting with free shape parameters the final shape parameters will be stored, accessible for later use.

The CARATE-FIT-1 commands are described in short form in Appendix E.

3.4. CARATE-GAUSS

During a long period of time, the fitting program GAUSS /Spa/, presented here, was used for batch mode analysis of multiplets at our laboratory. It was originally coded at the Van de Graaff laboratory at Utrecht.

At start of a GAUSS session, the program asks for the names of the spectrum input file and two files for output of results, one for a short-form table and the other for line-printer plots of accepted fittings. A default start-value for the full width at half maximum (FWHM) is also asked for.

For each peak (maximum 6) in the fitting interval defined by the user, GAUSS fits one Gaussian with an exponential tail at the low-channel side. A background is also included in the fit. At the start of a fit, all peaks are given the same full widths at half maximum, but then these parameters are fitted individually.

The command FIT will display the cross-hair cursor and accept single-character commands, described in Appendix F.

After a converging fit the user may save the results on a table output file and a line-printer plot file.

4. PROGRAMMING DETAILS

This section describes some details of the CARATE skeleton for the programming user who wants to slot his programs into CARATE and therefore needs to know the program code.

The labelled COMMON blocks and subprograms are described briefly below. The following abbreviations are used for definitions of variable types:

Abbreviation	Variable type
CH*n	CHARACTER*n
I	INTEGER
I*2	2 BYTE (=16 bits) INTEGER
I*4	4 BYTE (=32 bits) INTEGER
L	LOGICAL
R	REAL

4.1. Common blocks

```

/CARCOM/          CARATE global variables
KALL      CH*3    3-letter command, given by the user
REALIO(30) R      I/o buffer of subprograms CARIN and CAROUT
EN         I      Degree of calibration polynomial
E0         R
E1         R
E2         R
E3         R
DEFDAT     I*4    Default spectrum id-date YYMMDD when reading spectra
DISOFF     L      True when graphic display should be avoided
LINOFF     L      True when logarithmic scale is used in the display
SAVOFF     L      True when outputs on "result" file is inhibited
REAL       L      True when spectral data are stored as REAL

```

```

/COMCOM/          General communication
COMERR     L      True when an error has been detected
COMNUM     I      General purpose communication variable
COMMES     CH*80  Alphanumerical communication

```

```

/CURCOM/          Output from CARCXY
INC         I      ASCII code of the character pressed
INX         I      Screen x-coordinate of cross-hair cursor
INY         I      "      y-coordinate      "      "
IX          I      Channel number of vertical cursor line
X           R      "      "      "      "      "
Y           R      Number of counts corresponding to horiz.
                  cursor line

```

```

/IOUNIT/         Definitions of logical unit numbers
KIN           I      Terminal keyboard
KOUT          I      Terminal screen
LP            I      Line-printer
MT            I      Mag-tape station
SPIND         I      Input file for spectral data
SPINI         I      "      "      "      "      information
SPOUTD        I      Output file for spectral data
SPOUTI        I      "      "      "      "      information
OUT1          I      Output file 1
OUT2          I      "      "      2

```

```
/SHOW/      Display parameters. Coordinates in screen units.
XORIGO      I  x-coordinate for lower left corner of graphics area
YORIGO      I  y-coordinate " " " " " " " "
XAXLEN      I  Width of graphics area
YAXLEN      I  Height " " " "
ILEFT       I  Channel number of left limit of r-o-i
IRIGHT      I  " " " right " " "
IWIDTH      I  Number of channels in the r-o-i
XSTEP       R  Screen units/channel
YBIAS       R  Number of counts at baseline of last histogram drawn
YMAX        R  Top value of last histogram
YSCALE      I  Screen units/count in last histogram
IOXPOS      I  Current x-coordinate of text cursor
IOYPOS      I  " y-coordinate " " "
IOYHOM      I  Cursor y-coordinate at top of dialogue area
NOUPAY      I  Vertical size of characters
NOUPXC      I  Width of dialogue area
NCHPS       I  Transmission rate ( characters/sec ).
```

```
/SPIOCO/    Standard spectrum area
SPLOYR      I*2  YY
SPIOND      I*2  MMDD of spectrum identification date YYMMDD
SPIONR      I*2  NNN
SPIONC      I*2  Number of channels
SPIOND      I*2  Spectrum creation code, defining SPIOSP below.
SPIOEN      I*2  Degree of spectrum calibration polynomial
SPIOE0      I*4
SPIOE1      I*4
SPIOE2      I*4
SPIOE3      I*4
SPIOFA      I*4  100000*normalisation factor (special applications)
SPIOSP(36) I*2  Reserved for format-dependent parameters
SPIOUS(36) I*2  Free space for user's applications
SPIONI(40) I*2  Title (written in 40A2)
^PIODA      R    Spectral data array.
,4096)
```

4.2. Subprograms for graphic display

Only SUBROUTINE subprograms for basic operations are used. These are taken from TEKTRONIX Plot 10 Terminal Control System (TCS) and are described below. Coordinates are given in screen units with the range 0-1023 points on the horizontal axis and 0-779 on the vertical axis.

ANMODE

Dumps the graphics output buffer and switches to text mode.

BELL

Rings the terminal's bell

DRWABS(IX,IY)

Draws a line to (IX,IY).

DRWREL

Draws a line to a point with a displacement IX,IY.

ERASE

Erases the screen without changing terminal mode or beam position.

INITT(NCHPS)

Initializes by

- a) erasing screen and moving cursor to upper left corner,
- b) setting terminal in alpha - numeric mode.

Must be first call to TCS. NCHPS is the transmission rate in characters per second.

MOVABS(IX,IY)

Moves the beam to (IX,IY)

MOVREL(IX,IY)

Moves the beam to a point with a displacement of IX,IY.

NEWPAG

Erases screen and positions text cursor at the upper left corner.

SCURSR(ICHAR,IX,IY)

Activates graphic cursor, so the cursor can be positioned at any point. Returns ICHAR (the ASCII of the keyboard character pressed) and the cursor's coordinates IX,IY.

CARAPP(MODE)

This is the application subprogram.

Draws a cross at (IX,IY) to mark a position.

Gives values to the variables in COMMON/CURCOM/: Activates the cross-hair cursor and waits for one character INC from the keyboard. The screen coordinates of the cursor are then given by (INX,INY). The corresponding channel number as INTEGER (IX) and REAL (X) are calculated, and finally the number of counts as REAL Y is found from SPIODAI(X).

```

XORI      I      abscissa of lower left corner of histogram
YORI      I      ordinata " " " " " "
XAXL      I      length of x-axis in screen coordinates
YAXL      I      " " y-axis " " " "
IARR(1)   I*4    data array
ARR(1)    R      data array
YMA       R      upper limit in r-o-i
YMI       R      lower " " " "

```

Draws frames for one r-o-i area. If YMA or YMI are equal to zero, they are calculated from IARR or ARR, depending on the value of the variable REAL in COMMON/CARCOM/. From these values and the lengths of the axes, the scale factors are calculated. Finally the histogram is drawn and the limits of the r-o-i are written on the screen.

Erases the screen, calls CARDRW for drawing the histogram of SPIODA within the r-o-i. Finally it writes the standard command menu.

```
TEXT  CH*80 character string to be written in the
        dialogue area
NUMBER  I number of variables REALIO(I) to read
```

Positions the text cursor for alpha-numeric output, writes

the character string TEXT and reads REALIO(I), I=1,NUMBER in COMMON/CARCOM/. The text cursor coordinates are updated before exit.

CARLIM

Checks proposed new limits REALIO(1) and REALIO(2) in COMMON/CARCOM/ for region of interest. If the limits are accepted, CARHIS is called to show the new region of interest. Finally the application subprogram is called to reset its parameters to their default values and to write its special command menu. If the limits are not acceptable, COMERR is flagged, COMMES gets the text 'LEFT,RIGHT,MAX' and REALIO(3) the number of channels in SPIODA, thus preparing an error message for CAROUT

CARLIS(MODE)

MODE I controls the exit mode:=1 waits for <RETURN>

This subprogram is used to write a table of content of the input file. First the screen is erased, headlines are written and finally one line of information is written for each spectrum in the input file. If MODE=1 the user is asked to press the <RETURN> key to continue processing, thus giving him the opportunity to study the table of content.

CAROUT(TEXT,NUMBER)

TEXT CH*80 character string to output
NUMBER I number of real values to output

Positions the text cursor, writes the string TEXT and REALIO(I), I=1,NUMBER using FORMAT(2F10.2). Finally the cursor coordinates are updated.

CARSPE(MODE,ISP)

MODE I

- 1: open a file for spectrum read/write
- 2: open an input file for spectrum read only
- 3: open a file for spectrum write
- 4: virginize the spectrum output file
- 5: write spectrum
- 6: read spectrum
- 7: erase one spectrum
- 8: dump table of content
- 9: " " (short title)
- 10: identifier of spectrum COMNUM into COMMES
- 11: find and specify (in COMNUM) number of spectra in input file
- 12: read spectrum with index=COMNUM

ISP I*2 first word in the COMMON block
for spectral data

This subprogram is the only contact with the spectrum input/output handler subprogram SPI02, which may be very dependent on the system used.

5. HARDWARE

A CARATE program is run from a standard graphic display terminal equipped with graphic input facilities. Since alpha-numeric outputs are made after positioning the text cursor properly, no unsolicited movements of the cursor are acceptable. During graphic input operations, the user should press only one single button on the keyboard for each operation. The following strapping of a Tektronix terminal has been found to give the appropriate actions with a NORD-100 as host computer:

GIN TERMINATORS:	CR
DEL IMPLIES LOY:	YES
LF EFFECT:	LF
CR EFFECT:	CR ONLY

Maximum life for the terminal screen can be obtained by the following: (1) Keep the terminal turned off when not in use; (2) Do not maintain a stored display for more than 15 minutes; maintaining a stored display for longer periods may damage the screen; (3) Do not leave the terminal having the cross-hair cursor activated; the automatic reduced-intensity feature of the terminal is

then inoperative.

In order to get the correct delay time after an erasure of the screen, the transmission rate between terminal and computer must be set correctly by the application program as described in Section 4.

The memory requirement for the CARATE code without application subprograms is ~ 17000 of 16 bit words and the common areas occupy ~ 12700 words.

REFERENCES

- Bev P. R. Bevington, Data reduction and error analysis for the physical sciences, McGraw-Hill Book Company, 1969.
- Dav W. C. Davidon, Variable metric method for minimization, Argonne National Laboratory report ANL-5990, 1959;
E. Beals, VARMIT, Lawrence Radiation Laboratory memo BKY-20 (unpublished)
- Led C. M. Lederer, private communication
- Mar D. W. Marquardt, J. Soc. Ind. Appl Math,
vol. 11, no. 2 (1963) 431.
- Nei M. Neiman, private communication
- Spa R. Sparks, P. Ekström, J. Tillman, private communication

APPENDIX A: HOW TO RUN CARATE PROGRAMS AT LUCAS

The CARATE programs described above may be run from any Tektronix-compatible terminal connected to the NORD-100/500 computer system LUCAS. The programs are available in :PROG versions under user SYSTEM, which means that they are started by issuing their names.

PROGRAMS FOR STORAGE OF SPECTRA IN CARATE-READABLE FORMAT

The following programs are all written for interactive run on the LUCAS computer system. They present themselves by asking for the name of an output file which is assumed to already exist at the computer subsystem under use. New such files are created by the following commands to the operating system:

CREATE-FILE file-name:SPID 0

CREATE-FILE same name:SPDA 0

The programs then give a self-explanatory menu of commands. Only the three first characters of the commands are used. (The SPIOID code is of interest only for the programming user!)

PROGRAM NAME	INPUT SOURCE
AFISPE	Magnetic tapes written at Research Institute for Physics, Stockholm, Sweden (SPIOID=3).
ND6620	Magnetic tapes written on a Nuclear Data ND6620 System (SPIOID=1).
NUDATA	Direct transfer from the Nuclear Data ND6620 System at the Pelletron Laboratory (SPIOID=6)
RISOSP	Magnetic tapes written at the Niels Bohr Institute, Riso, Denmark (SPIOID=2).
SEXTON	Magnetic tapes written at the Computer Center, University of Lund. This program reads spectra written in ANNLIIS format /Eks/ with sixteen bits/channel (SPIOID=5).
UNIPSE	Magnetic tapes written at the Computer Center, University of Lund. This program reads spectra written by the program LUCASP in ANNLIIS format /Eks/ with 32 bits/channel (SPIOID=4).

REFERENCE:

Eks P. Ekström, I. Mauritzson and J. Tillman,
 Nuclear Physics Report, LUNP 7101,
 Lund University, 1971.

APPENDIX B: MAIN MENU

CALIBRATE

Accepts degree of calibration polynomial and its coefficients.

CHANNEL

Reads left and right limit for r-o-i (in channel number). Displays the specified region. Reset parameters in application program to their default values.

CURSOR

Displays cursor, accepts graphical input of channel number and types channel number, calibration units and number of counts of the specified channel.

DEFAULT

Redisplays the r-o-i. Resets parameters in the application program to their default values.

GET

Gets spectrum from the input file to the data area and displays the r-o-i.

GRAPHIC

Displays cross-hair cursor, accepts graphic inputs of limits for the r-o-i. Displays the region. Resets parameters in the application program to their default values.

INDATE

Accepts default identity date for input spectra (if 0: no default date)

LIST

Shows table of content of the input file.

LIN/LOG

Switches the log-scale off/on.

MARKER

Draws a marker at a channel within the r-o-i, defined in units of calibration.

SAVE

Switches table outputs on/off.

TAG

Types table of content of input file, displays cursor, accepts graphical input of a spectrum specification by its tag number (1-9). Exits when a non-numerical key is pressed.

QUIT

Exits CARATE and returns to the operating system.

ROI

Reads left and right limits for r-o-i (in units of calibration). Displays the specified region. Resets parameters in the application program to their default values.

WIPE

Redisplays the r-o-i. Parameters in the application program are unchanged.

APPENDIX C: CARATE-MANIPU COMMANDS

COMMANDS ACCEPTABLE FOR CARATE-MANIPU: 3-CHARACTER COMMANDS

COMMAND PARAMETERS; OPERATIONS

ACCEPT Spectrum id; reads spectrum to output buffer.
ADD Id + factor F; spectrum to input buffer; $OUT = OUT + F * IN$.
BACK- YYMMDD, bunch N and bias B, then PPP,BB1,FF1,BB2,FF2,
-GROUND title.
BIAS Bias B; then $OUT = OUT + B$.
BUNCH Channels/bunch N;
 $OUT(I) = OUT(J+1) + \dots + OUT(J+N), J = (I-1) * N$.
CALIBRATE Degree and coefficients of calibration polynomial for
 channel axis.
CHANNEL Limits for r-o-i; displays it.
CLEAR ;OUT=0.
COPY Id; reads spectrum to output buffer, writes it on output
 file.
CURSOR ;Displays cross-hair cursor to get a channel number and
 types channel number,energy and number of counts of
 the channel.
DEFAULT ;Erases the screen and redisplayes r-o-i.
DISPLAY ;Switches graphic display on/off.
GET Id; reads spectrum to input buffer.
GRAPHIC ;Displays cross-hair cursor, accepts graphical input
 of limits for r-o-i and displays it. Resets parameters
 to default values.
INDATE Default id-date for input spectra (if 0: no default).
INPUT Start channel I, number of channels N;
 reads $OUT(I), OUT(I+1), \dots, OUT(I+N-1)$.
LIST ;Shows table of content of the input file.
LOG-LIN ;Switches the log-scale on/off.
MARKER Channel in calibration units; draws a cross at that
 channel.
MULTIPLY F; $IN = F * IN$.
NUMBER NNN of next spectrum that will be written on the output
 file.
OUTDATE Identity date for next output spectrum.
PRINT Start and stop channels for printout;
 prints channel contents of the output buffer.
QUIT ;Exits CARATE and returns to the operating system.
ROI R-o-i limits in calibration units; displays it.
SAVE Switches the table outputs on/off.
SHIFT Number of channels N to shift; $IN(I) = IN(I-N)$.
SHOW ;Shows the r-o-i of the output buffer.
SMOOTH ;Performs a three-channel smoothing.
SUBTRACT Id, F; reads spectrum into input buffer, $OUT = OUT - F * IN$.
TAG ;Shows table of content of input file, displays
 cursor, accepts graphical spectrum specification
 and its tag number (1-9).
TRANSFER ;OUT = OUT + IN.
TYPE Left and right channel limits; types channel
 contents on the screen.

<u>WIPE</u>	;Erases and redisplay the r-o-i.
<u>WRITE</u>	;Writes the output buffer on the output file.

APPENDIX D: CARATE-SUSIE COMMANDS

COMMANDS ACCEPTABLE FOR CARATE-SUSIE: 3-CHARACTER COMMANDS

COMMAND PARAMETERS; OPERATIONS

<u>CALIBRATE</u>	Degree of calibration polynomial and its coefficients.
<u>CHANNEL</u>	Limits for r-o-i; displays and resets parameters.
<u>CURSOR</u>	Displays cross-hair cursor to get a channel number and types channel number, energy and number of counts of the channel.
<u>DEFAULT</u>	Erases and redisplay the r-o-i. Resets fit parameters to their default values.
<u>FIT</u>	Enters fit mode, displays cross-hair cursor and accepts single-character commands.
<u>GET</u>	Id; reads spectrum from input file and displays the r-o-i.
<u>GRAPHIC</u>	;Displays cross-hair cursor, accepts graphical input of limits for the r-o-i. Resets fit parameters to default values.
<u>INDATE</u>	Default identity date for input spectra (if=0: no default).
<u>LOG-LIN</u>	;Switches the log-scale on/off.
<u>LIST</u>	Shows table of content of the input file.
<u>MARKER</u>	Channel in calibration units; draws a cross at that channel.
<u>QUIT</u>	;Exits CARATE and returns to the operating system.
<u>ROI</u>	R-o-i limits in cal. units; displays and resets parameters.
<u>SAVE</u>	;Switches the table outputs on/off.
<u>TAG</u>	;Shows table of content of input file, displays cursor, accepts graphically spectrum specification and its tag number (1-9).
<u>WIPE</u>	;Erases and redisplay r-o-i, parameters unchanged.

COMMANDS ACCEPTABLE FOR CARATE-SUSIE: SINGLE-CHARACTER COMMANDS

CMD MNEMONIC EXPLANATION

D	Default	Erases and redisplay r-o-i using default parameters.
E	End	End channel of fit region.
L	Linear	Fits with a linear or quadratic background.
N	Numeric	Reads FWHM.
P	Peak	Start value of an additional peak position.
R	Return	Returns to the main menu.
S	Start	Start channel of fit region.
W	Wipe	Erases and redisplay r-o-i.
Y	Yes	Saves results from the last fit.

APPENDIX E: CARATE-FIT-1 COMMANDS

COMMANDS ACCEPTABLE FOR CARATE-FIT-1: 3-CHARACTER COMMANDS

COMMAND PARAMETERS; OPERATIONS

CALIBRATE Degree of calibration polynomial and its coefficients.
CHANNEL Limits for r-o-i; displays r-o-i and resets parameters.
CURSOR Displays cross-hair cursor to get a channel number and types
channel number, energy and number of counts of the channel.
DEFAULT Erases and redisplayes the r-o-i, resets fit parameters to
their default values.
FIT Enters fit mode, displays cross-hair cursor and accepts
single-letter commands.
GET Spectrum identification; reads spectrum from input file
and displays the r-o-i.
GRAPHIC ;Displays cross-hair cursor, accepts graphical input of
limits for the r-o-i. Resets fit parameters to default
values.
INDATE Default identity-date for input spectra (if =0: no default)
LOG-LIN Switches the log-scale on/off.
LIST Shows table of content of the input file.
MARKER Channel in calibration units; draws a cross at that channel.
QUIT ;Exits CARATE and returns to the operating system.
RESET ;Resets the shape library.
ROI R-o-i limits in cal. units; displays and resets parameters.
TAG ;Shows table of content of input file, displays cursor,
accepts graphically spectrum specification and its
tag number (1-9).
WIPE ;Erases and redisplayes r-o-i, parameters unchanged.

COMMANDS ACCEPTABLE FOR CARATE-FIT-1: SINGLE-CHARACTER COMMANDS

CMD MNEMONIC EXPLANATION

D Default Erases and redisplayes r-o-i, resets parameters to
the default values.
E End End channel of fit region.
F Fix Fits with a linear, fixed background through endpoints.
I Include Includes next peak in the shape library.
L Linear Fits with a linear background.
N Numeric Reads FWHM and tail parameters.
P Peak Start value of an additional peak position.
R Return Returns to the main menu.
S Start Start channel of fit region.
U Uncert Types uncertainties in the last fit.
W Wipe Erases and redisplayes r-o-i.
Y Yes Saves results from the last fit.

APPENDIX F: CARATE-GAUSS COMMANDS

COMMANDS ACCEPTABLE FOR CARATE-GAUSS: 3-CHARACTER COMMANDS

COMMAND PARAMETERS; OPERATIONS

CALIBRATE Degree of calibration polynomial and its coefficients.
CHANNEL Limits for r-o-i; displays and resets parameters.
CURSOR Displays cross-hair cursor to get a channel number and types
channel number,energy and number of counts of the channel.
DEFAULT ;Erases and redisplayes the r-o-i, resets fit parameters
to their default values.
FIT Enters fit mode, displays cross-hair cursor and accept
single-letter commands.
GET Id; reads spectrum from input file and displays the r-o-i.
GRAPHIC ;Displays cross-hair cursor, accepts graphical input of
limits for the r-o-i,displays r-o-i, resets fit parameters
to default values.
INDATE Default id-date for input spectra (if 0: no default).
LIST Shows table of content of the input file.
LOG-LIN Switches the log-scale on/off.
MARKER Chnl in calibration units; draws a cross at that channel.
QUIT ;Exits CARATE and returns to the operating system.
ROI R-o-i limits in cal. units; displays and resets parameters.
SAVE Switches the table outputs on/off.
TAG ;Shows table of content of input file, displays cursor,
accepts graphically spectrum specification and its
tag number (1-9).
WIPE ;Erases and redisplayes r-o-i, parameters unchanged.

COMMANDS ACCEPTABLE FOR CARATE-GAUSS: SINGLE-CHARACTER COMMANDS

CMD MNEMONIC EXPLANATION

D Default Erases and redisplayes, resets fit parameters to
 default values.
E End End channel of fit region.
N Numeric Reads default FWHM.
P Peak Start value of an additional peak position.
Q Quadr Fits with quadratic background.
R Return Returns to the main menu.
S Start Start channel of fit region.
W Wipe Erases and redisplayes r-o-i.
Y Yes Saves results from the last fit.

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CARATE

A program package for interactive treatment of one-dimensional spectra.

Referat (sammandrag)

CARATE is a program package for interactive use of spectral analysis codes. This report describes its general outlines and how to run four different applications from a standard graphic display terminal connected to a medium-sized mini-computer. FORTRAN77 is used and programming details are given to facilitate new implementations.

Referat skrivet av

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Pris

High Spin Shell Model Excitations in ^{149}Gd

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The high spin level structure of the three-neutron nucleus ^{149}Gd has been investigated by in-beam γ -ray and electron spectroscopy with (α, xn) reactions. The observed levels are characterized as members of the shell model multiplets $\nu f_{7/2}^3$, $\nu h_{9/2} f_{7/2}^2$, $\nu f_{7/2}^3 \times 3^-$, $\nu h_{9/2} f_{7/2}^2 \times 3^-$, and tentatively $\nu f_{7/2}^3 \times (3^-)^2$. The energies of the $\nu f_{7/2}^3$ states agree only moderately with those calculated using empirical two-nucleon interactions taken from ^{148}Gd , which indicates the importance of long range contributions already at $N=85$.

1. Introduction

In a number of recent studies of the high spin states in nuclei around ^{146}Gd it has been shown [1-4] that this nucleus can act as a doubly closed core. This means that its yrast levels and those of other nuclei in this region can be described using techniques based on the spherical shell model similar to those which have been successfully applied in the ^{208}Pb region [5]. In the present study we have investigated the high spin levels in the ^{149}Gd nucleus which has three neutrons outside the ^{146}Gd core. From previous investigations [1, 6] the high spin states in the one- and two-neutron nuclei ^{147}Gd and ^{148}Gd are fairly well known. From this experimental information it should be possible - using the shell model - to calculate the high spin excitations for the three-neutron nucleus ^{149}Gd provided that the relevant ground state masses are known. On the other hand, the Gd isotopes with $N \geq 89$ are known to be strongly deformed, and deformed configurations

have been identified [7] in ^{151}Gd and other $N=87$ nuclei. A study of ^{149}Gd is therefore of interest since it will show to what extent the spherical shell model can describe the $N=85$ nuclei.

Of particular interest in this region are the octupole excitations, which at $N \approx 82$ are lowest for Gd since here the Fermi energy lies between the $d_{5/2}$ and $h_{11/2}$ proton orbits. When more neutrons are added $\nu f_{7/2} i_{13/2}$ transitions will add to the octupole strength and further lower its energy. This unusually low octupole energy favours the observation of two-phonon octupole excitations; in ^{147}Gd a $19/2^-$ state has been suggested [1] to be predominantly of $\nu f_{7/2}^3 \times 3^- \times 3^-$ character. In the present study we have identified a group of levels in ^{149}Gd which might be associated with an analogous $\nu f_{7/2}^3 \times 3^- \times 3^-$ excitation.

The energy levels of ^{149}Gd have previously been investigated in β -decay [8-10] of ^{149}Tb and ^{149m}Tb , but only few of the states observed in these studies are also populated in the present in-beam experiments. In an earlier $(\alpha, 3n)$ study [11] a few high-spin states associated with the $13/2^+$ level at

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956 keV have been reported. After completion of our measurements we have become aware of an independent in-beam study of ^{149}Gd , with the $(\alpha, 2n)$ and $(^{11}\text{B}, 3n)$ reactions, which is reported [12] in a recent annual report. The level scheme of that work in many aspects agrees with our own results which have previously been reported in [13 and 14].

2. Experiments

In the present work we have investigated the ^{149}Gd nucleus by in-beam γ - and electron-spectroscopy using the $(\alpha, 3n)$, $(\alpha, 4n)$, and $(\alpha, 5n)$ reactions. The $(\alpha, 3n)$ and $(\alpha, 5n)$ experiments were carried out at the cyclotron at Jülich with beam energies of

Table 1. Gamma transitions in ^{149}Gd observed in the $^{150}\text{Sm}(\alpha, 5n)$ reaction at 67 MeV bombarding energy

E_γ (keV)	Rel. γ -ray intensity ^a	Ang. distr. coeff. ^b		P^c	Placement	
		A_2	A_4		E_γ (keV)	$I_i^\pi \rightarrow I_f^\pi$
77.6(1)	178	-0.20(2)	-0.04(3)		873.5	$11/2^+ \rightarrow 9/2^-$
82.5(1)	101	-0.28(3)	-0.05(4)		956.0	$13/2^+ \rightarrow 11/2^+$
98.2(1)	177	0.31(1)	-0.00(1)		873.5	$11/2^+ \rightarrow 11/2^-$
159.6(1)	90	0.28(1)	-0.06(2)		3,387.5	$27/2^+ \rightarrow 23/2^+$
165.1(3)	25	0.10(3)	0.01(4)		165.1	$5/2^- \rightarrow 7/2^-$
180.6(1)	129	-0.23(1)	-0.01(1)		956.0	$13/2^+ \rightarrow 11/2^-$
245.1(2)	28	0.33(4)	0.03(6)		3,632.6	$27/2^+ \rightarrow 27/2^-$
248.1(3)	107 ^d	-0.15(1) ^d	0.00(2) ^d		4,572.4	$(31/2^-) \rightarrow (29/2^-)$
292.5(3)	48	0.32(2)	-0.09(3)		2,524.3	$21/2^- \rightarrow 17/2^-$
325.5(3)	25	-0.38(4)	-0.01(6)		2,383.8	$19/2^- \rightarrow 17/2^-$
337.8(2)	37	-0.38(3)	-0.04(5)		3,632.6	$27/2^+ \rightarrow 25/2^+$
378.2(3)	44	-0.14(3)	-0.01(4)		3,765.7	$29/2^- \rightarrow 27/2^+$
422.8(2)	64	-0.29(2)	0.02(3)			
449.0(2)	39	0.37(3)	-0.05(5)		2,058.3	$17/2^- \rightarrow 13/2^-$
454.9(2)	75	0.26(2)	-0.01(3)		2,856.6	$\rightarrow 21/2^+$
466.0(2)	217 ^e	0.31(2) ^e	-0.03(3) ^e	-0.08(4)	2,524.3	$21/2^- \rightarrow 17/2^-$
499.5(3)	78	0.33(2)	-0.00(3)			
528.0(1)	105	-0.23(2)	0.03(2)		1,484.1	$15/2^- \rightarrow 13/2^+$
574.2(1)	214	-0.21(1)	0.01(1)	0.12(3)	2,058.3	$17/2^- \rightarrow 15/2^-$
622.6(3)	30	0.01(6)	-0.02(8)		2,231.8	$17/2^- \rightarrow 13/2^-$
630.4(5)	$\sim 49^f$	0.23(3) ^f	-0.07(4) ^f		795.9	$9/2^- \rightarrow 5/2^-$
643.7(2)	45	-0.19(4)	-0.05(5)		2,383.8	$19/2^- \rightarrow 17/2^-$
661.4(1)	360	0.30(1)	-0.08(1)	-0.06(3)	2,401.7	$21/2^+ \rightarrow 17/2^+$
683.3(2)	36	-0.95(4)	-0.02(6)		3,085.0	$23/2^- \rightarrow 21/2^+$
703.6(2)	101 ^g	-0.21(3) ^g	0.00(3) ^g	-0.08(9)	3,227.9	$23/2^- \rightarrow 21/2^-$
708.8(1) ^h	344 ^h	0.34(1)	-0.06(1)	-0.09(3)	1,484.1	$15/2^- \rightarrow 11/2^-$
712.3(2)	79	0.39(2)	-0.10(3)		4,324.3	$(29/2^-) \rightarrow 25/2^-$
733.1(4)	35	-0.16(4)	-0.07(6)		3,134.8	$23/2^- \rightarrow 21/2^+$
747.5(5)	$\sim 39^i$	0.18(1) ⁱ	-0.02(2) ⁱ		2,231.8	$17/2^- \rightarrow 15/2^-$
750.8(5)	58	0.29(2)	-0.08(3)		3,134.8	$23/2^- \rightarrow 19/2^-$
775.3(1)	641	0.26(1)	-0.05(1)	-0.09(2)	775.3	$11/2^- \rightarrow 7/2^-$
784.3(3)	427 ^j	0.27(1)	-0.06(1)	-0.10(2)	1,740.3	$17/2^+ \rightarrow 13/2^+$
795.9(1)	334	0.07(1)	0.03(1)	0.16(5)	795.9	$9/2^- \rightarrow 7/2^-$
813.3(2)	48	0.22(4)	-0.08(5)		1,609.3	$13/2^- \rightarrow 9/2^-$
826.4(4)	16				3,227.9	$23/2^+ \rightarrow 21/2^+$
834.2(3)	37	-0.16(3)	-0.02(4)		1,609.3	$13/2^- \rightarrow 11/2^-$
863.0(4)	15	0.54(8)	0.14(12)		3,387.5	$27/2^- \rightarrow 21/2^-$
893.2(1)	148	0.32(1)	-0.08(2)		3,294.9	$25/2^+ \rightarrow 21/2^+$
899.6(2)	44	0.28(3)	0.01(5)		2,383.8	$19/2^- \rightarrow 15/2^-$
1,087.7(1)	124	0.34(2)	-0.09(3)	-0.12(6)	3,612.0	$25/2^- \rightarrow 21/2^-$

^a Measured at $\theta = 125^\circ$; error $\sim 5\%$ larger for weak or unresolved lines

^b Errors are pure fit errors

^c Counting rate asymmetry $P = (N_0 - N_1)/(N_0 + N_1)$. Polarization data measured with the $^{149}\text{Sm}(\alpha, 4n)$ reaction at 51 MeV

^d Data uncertain, not resolved from a degenerate background line

^e Data corrected for 6% contribution from 465.6 keV $M1$ transition in ^{148}Gd

^f Obscured by the strong 631.9 keV transition in ^{148}Gd

^g Data corrected for 28% contribution from 704.0 keV $E2$ transition in ^{150}Gd

^h Doublet; the weak component also belongs to ^{149}Gd but is not placed in the level scheme

ⁱ Obscured by the intense 747.2 keV line in ^{146}Sm . Intensity derived from coincidence data

^j Intensity corrected for 40% contribution from 784.5 keV $E2$ transition in ^{148}Gd

44 MeV and 67 MeV; 51 MeV α particles from the Stockholm cyclotron were used in the $(\alpha, 4n)$ measurements.

The γ -ray angular distributions were measured in two independent experiments, with the $(\alpha, 5n)$ reaction and with the $(\alpha, 4n)$ reaction, covering the $90^\circ \leq \theta \leq 165^\circ$ range. The two sets of data were in excellent agreement. In Table 1 we have listed the results of the $(\alpha, 5n)$ measurements except for a few transitions where the $(\alpha, 4n)$ data had cleaner spectra. An example of a γ -ray singles spectrum is shown in Fig. 1.

Detailed γ -ray excitation functions were measured for the $(\alpha, 4n)$ reaction using five bombarding energies between 42 and 53 MeV.

Two $\approx 70 \text{ cm}^3$ true coaxial Ge(Li) detectors were used in a four-parameter γ -ray list mode coincidence experiment ($E_1, E_2, t_{12}, t_{1RF}$). Both counters were placed at 125° to the beam direction and shielded from each other to exclude coincidences due to backscattered γ -rays. The $^{148}\text{Sm}(\alpha, 3n)$ reaction was used for these measurements because it provided the cleanest selection of the ^{149}Gd exit channel. Examples of these data are shown in Fig. 2. A separate $\gamma\gamma$ -coincidence measurement with the $(\alpha, 5n)$ reaction brought no additional information.

The $\gamma\gamma$ -coincidence results did not reveal isomers with $T_{1/2} \geq 10 \text{ ns}$ in ^{149}Gd . To find shorter-lived isomers a three-parameter timing coincidence experiment was performed with a 2 cm^3 Ge detector in coincidence with a $5 \times 7.5 \text{ cm}$ NaI (Tl) scintillation detector. For each event the γ -ray energy in the Ge-detector and the time delays relative to the beam bursts for both detectors were list mode recorded.

This measurement identified two half lives. A $T_{1/2} = 6.0(5) \text{ ns}$ isomer was observed in the decay curves of a number of γ transitions (cf. Fig. 3) and could from these data be placed at $E_x = 3,388 \text{ keV}$. A second, much shorter half life was determined from the centroid shifts measured for two pairs of intense γ rays, v.z. the 83–78 keV and 83–98 keV transition pairs (Fig. 3). The two measurements gave the result $\tau = 2.3(8) \text{ ns}$, corresponding to a half life of $T_{1/2} = 1.6(6) \text{ ns}$ for the isomer at 874 keV. The centroids of these time distributions depend on the fraction of the feeding intensity proceeding via the 6 ns isomer. In the $\pm 0.8 \text{ ns}$ experimental error the different side feeding intensities to the 874 keV and 956 keV levels have been taken into account.

A γ -ray linear polarization measurement was made using two separate Ge(Li) detectors, one of them heavily shielded against target γ -rays, placed at 8 cm distance from each other and 25 cm below the target. Coincidences between them were list mode recorded. A third detector in a fixed position served to normalize the intensities measured for the parallel and perpendicular positions of the polarimeter.

In the polarization measurement the 704 keV γ -line, which is of crucial importance for determination of the parity of the 6.0 ns isomer, could not be resolved. We have therefore measured its α_K value using an orange spectrometer [15] with a momentum resolution of $\Delta p/p = 0.7\%$. In this measurement the close lying intense 661 keV $E2$ transition was used to normalize e^- and γ intensities. The result, $\alpha_K < 6.5 \times 10^{-3}$, together with the measured angular distribution, clearly establishes $E1$ character for the 704 keV transition.

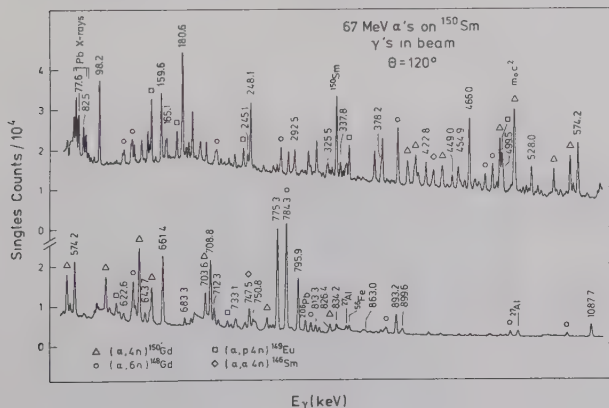


Fig. 1. Gamma-ray spectrum observed with a 65 cm^3 Ge(Li) detector during bombardment of ^{150}Sm with 67 MeV α particles. Energies are given for the ^{149}Gd γ rays populated through $(\alpha, 5n)$

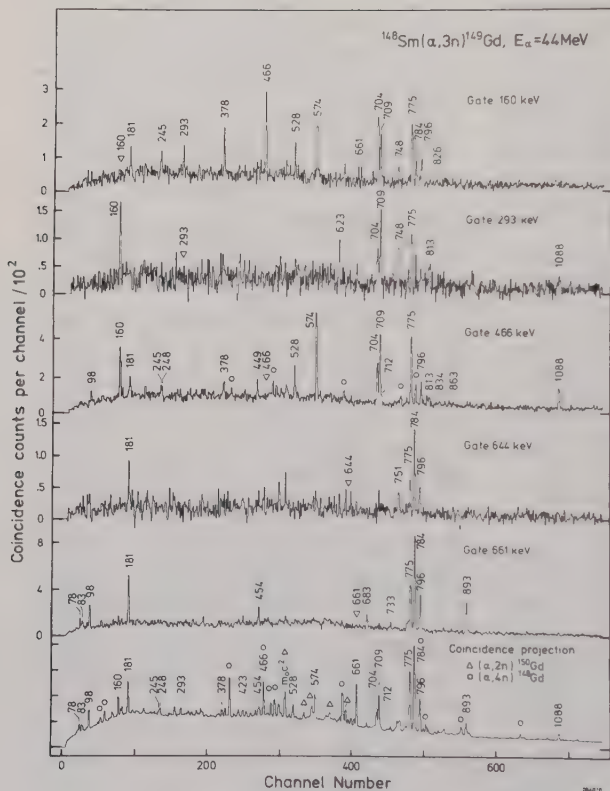
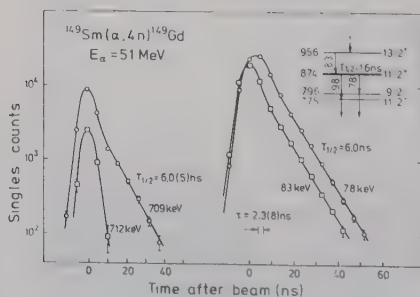


Fig. 2. Selected prompt coincidence spectra ($\Delta t_{1,2} \approx 50$ ns) for ^{149}Gd measured during ± 20 ns intervals centered on the 140 ns separated beam bursts. The bottom spectrum shows the coincidence projection with no restriction on the two time parameters



3. Level Scheme and Spin-Parity Assignments

From atomic beam experiments [16] a ground state spin of $7/2$ has been determined for ^{149}Gd , and negative parity is inferred from the shell model.

The $T_{1/2} = 4.2$ min $^{149\text{m}}\text{Tb}$ isomer attributed [8] to the $\pi h_{11/2}$ configuration β -decays with $\log f t \approx 4.4$ to a level in ^{149}Gd at 796 keV, which therefore is char-

Fig. 3. Examples of t_{RP} timing measurements for selected ^{149}Gd γ transitions. Both figures show the $T_{1/2} = 6.0$ ns half life; to the left a distribution of a prompt transition (712 keV) is included for comparison. The centroid shift extracted from the two curves to the right gives the $T_{1/2} = 1.6$ ns half life for the 874 keV level

acterized as $vh_{9/2}$ one particle excitation. This level is strongly populated in the present study. The level predominantly deexcites to the $vf_{7/2}$ ground state; a weak branch proceeds through a level at 165 keV, which from the β -decay of 4.2 h ^{149}Tb has been assigned [10] as $5/2^-$ state. The β -decay work has established numerous other levels, but they are not observed in our experiments.

The results of the measurements described in the preceding section establish the level scheme of Fig. 4. In most cases the angular distribution and polarization data, together with the observed branching ratios and $T_{1/2}$ limits, provide unambiguous spin and parity assignments. Intensity balance arguments have been used to determine the parity of the 874 keV level. The only possible multiplicities are $M1$ for the 83 keV feeding γ -ray, and $E1$ for the two 78 and 98 keV depopulating transitions. This gives positive parity for the 874 and 956 keV states. The dipole character of the 528 keV and 181 keV transitions requires $I^\pi=13/2^+$ for the latter state. In the previous section we have already discussed the multiplicity of the 704 keV line. It determines $I^\pi=23/2^+$ for the 3,228 keV state and, with the $E2$ character of the 160 keV isomeric transition, $I^\pi=27/2^+$ for the 6.0 ns isomer at 3,388 keV.

4. Discussion

4.1. The $vf_{7/2}^3$ States

The ^{149}Gd has three valence neutrons above the $N=82$ shell, and the $7/2$ ground state spin suggests its interpretation as $(vf_{7/2}^3)_{7/2}$ state. The $(f_{7/2}^3)_{11/2}$ and $(f_{7/2}^3)_{15/2}$ states at 775 and 1,484 keV are yrast states and are strongly populated in the present experiments. Of the non-yrast $f_{7/2}^3$ multiplet members one knows [10] the $5/2$ state at 165 keV. The 352 keV $3/2^-$ level seen [10] in the 4.2 h ^{149}Tb β decay most likely also belongs to the $vf_{7/2}^3$ configuration. Moreover, the $f_{7/2}^3$ multiplet contains a $9/2$ member which has not been observed. This state will be further discussed below.

Using angular momentum algebra [17] the energies of the $f_{7/2}^3$ multiplet members can be calculated from the empirical energies of the $f_{7/2}^2$ quartet as observed [6] in the two-particle nucleus ^{148}Gd . In Fig. 5 these calculated energies are compared with the experimental energy levels of ^{149}Gd . The absolute level energies are evaluated using the mass parameter

$$E_0 = M(^{146}\text{Gd}) - 3M(^{147}\text{Gd}) + 3M(^{148}\text{Gd}) - M(^{149}\text{Gd}) = -3,571 \text{ keV}. \quad (1)$$

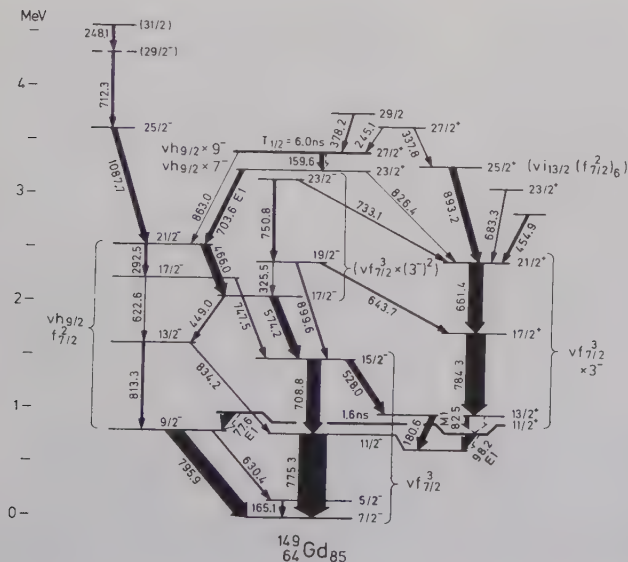


Fig. 4. Level scheme of ^{149}Gd established from the present in beam γ -ray studies. Transition intensities are drawn as observed in the (α, n) reaction, and multiplicities are given where conversion electron information is available. Proposed shell model configuration assignments are indicated

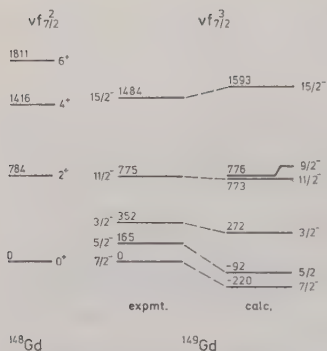


Fig. 5. Energies of the ^{149}Gd $\nu f_{7/2}^3$ states compared to the values calculated from the $\nu f_{7/2}^2$ states observed in the two-neutron nucleus ^{148}Gd

The mass values of the four nuclei are obtained from the 1977 mass tables [18] and from a recent analysis [19] of ground state masses in the ^{146}Gd region.

The agreement between calculated and experimental level energies is only moderate, even for the yrast multiplet members, which should be rather pure $f_{7/2}^3$ states. A similar calculation of the $\pi h_{9/2}^3$ levels [20] in ^{211}At agrees with experiment within 20 keV, and the level spacings calculated for the $\pi h_{9/2}^3$ yrast states in ^{149}Ho reproduce the experimental values [21] to $\lesssim 60$ keV. The comparison in Fig. 5 thus indicates that the shell model is no longer applicable here for accurate level energy calculations. This is in accord with the finding [19] that the $Z=64$ gap decreases rapidly when going from $N=82$ towards higher neutron number. At $N=86$ it has almost disappeared, and one therefore expects that quadrupole effects will significantly distort the $f_{7/2}^3$ energy spectrum. Nevertheless, the spherical shell model is still quite useful to describe the level spacings qualitatively.

4.2. The $\nu h_{9/2}$ Excitation and $\nu h_{9/2} f_{7/2}^2$ States

As we have mentioned in Sect. 3 the β decay data characterize [8] the 796 keV $9/2^-$ state as a $\nu h_{9/2}$ single-particle excitation. Similar β decay results have identified [22] the $\nu h_{9/2}$ state in ^{151}Dy at 527 keV. In the lighter isotones the $\nu h_{9/2}$ excitation is known from single neutron transfer experiments,

at 809 keV in ^{147}Sm [23], at 747 keV in ^{145}Nd [24], and at 668 keV in ^{143}Ce [25].

Additional support for the $\nu h_{9/2}$ interpretation comes from the γ decay data. The 796 keV state decays by $\geq 90\%$ to the $(\nu f_{7/2}^3)_{7/2}$ ground state, whereas a $(\nu f_{7/2}^3)_{9/2}$ level, also expected at ~ 0.8 MeV, should predominantly decay by an $E2$ transition to the $(\nu f_{7/2}^3)_{5/2}$ level at 165 keV. The fact that only the 796 keV level is observed in ^{149}mTb β decay indicates that the two $9/2^-$ levels are not strongly admixed. The very detailed study [10] of 4.2 h ^{149}Tb β decay has established a level at 1,086 keV with $I=5/2, 7/2$, or $9/2$ and negative parity which could be the missing $(\nu f_{7/2}^3)_{9/2}$ state.

With one valence neutron lifted to the $h_{9/2}$ orbital the two remaining $f_{7/2}^2$ neutrons can form the characteristic $(\nu f_{7/2}^2) 0^+, 2^+, 4^+, 6^+$ multiplet, giving rise to yrast levels with $I^\pi=9/2^-, 13/2^-, 17/2^-$, and $21/2^-$ which are all observed in the four isotones ^{147}Sm [26], ^{149}Gd , ^{151}Dy [27], and ^{153}Er [28]. The situation is somewhat complicated in ^{149}Gd since here two $17/2^-$ states are found, at 2,058 keV and 2,232 keV excitation. The complete $\nu h_{9/2} f_{7/2}^2$ multiplet contains in fact two $17/2^-$ levels, but one of them is expected to lie definitely above the $21/2^-$ member at 2,524 keV and therefore cannot be identified with one of the two observed $17/2^-$ levels. The measured γ -ray branchings indicate that the observed two $17/2^-$ levels are rather mixed, but we interpret the 2,232 keV state to have mainly $(\nu h_{9/2} f_{7/2}^2)_{17/2}$ character. Two arguments suggest this choice: Firstly, the 293 keV $E2$ transition is 2.3 times faster than the 466 keV transition, favouring the former as the intramultiplet transition. Secondly, we have compared the $(M1, 17/2^- \rightarrow 15/2^-)/(E2, 17/2^- \rightarrow 13/2^-)$ branching ratios for the two $17/2^-$ states to the values found [26, 27] in ^{147}Sm and ^{151}Dy where only one $17/2^-$ has been observed. The energy-corrected $M1/E2$ transition intensity ratios in ^{147}Sm and ^{151}Dy are 0.37(4) and 0.38(4) which compare well with the value 0.33(15) obtained for the upper $17/2^-$ state in ^{149}Gd , whereas the ratio for the lower $17/2^-$ state is 0.60(8). Finally, one would expect the $21/2^-$ to $17/2^-$ spacing of the $\nu h_{9/2} f_{7/2}^2$ multiplet to be smaller than the 6^+ to 4^+ separation of the $\nu f_{7/2}^3$ multiplet as observed in ^{148}Gd . This also favours assignment of the higherlying $17/2^-$ state as $\nu h_{9/2} f_{7/2}^2$.

To calculate the complete $\nu h_{9/2} f_{7/2}^2$ multiplet one would need empirical $\nu h_{9/2} f_{7/2}^2$ interaction energies for all possible spin values of this two-neutron multiplet. However, in ^{148}Gd only the 8^+ member is known [6]. Assuming that the $(\nu h_{9/2} f_{7/2}^2)$ interaction is about 0.3 MeV less attractive than the 8^+ interaction we can calculate the excitation energy of

the $21/2^-$ state in ^{149}Gd as

$$E_x((h_{9/2}2f_{7/2}^2)_{21/2}) = E_x((f_{7/2}^2)_6) + 1.44 E_x((h_{9/2}f_{7/2})_8) \\ + 0.56 E_x((h_{9/2}f_{7/2})_7) - E_x(h_{9/2}) + E_0 \approx 2.40 \text{ MeV}$$

which is in rather good agreement with the experimental excitation energy of 2.524 MeV. Here, E_0 is the same mass parameter as in (1), and the excitation energies for the two-neutron configurations are taken from ^{148}Gd . $E_x(h_{9/2}) = 1.398 \text{ keV}$ is the energy [29] of the $vh_{9/2}$ level in ^{147}Gd . The second and third terms give the contribution of the $vh_{9/2}f_{7/2}$ residual interaction to the $21/2^-$ energy; the numerical factors are angular momentum recoupling coefficients.

4.3. The $27/2^+$ 6.0 ns Isomer at 3,388 keV

In ^{148}Gd a 9^- isomer with 17.5 ns half life at 2,695 keV has been interpreted [6] as the $(3^- \times (vf_{7/2}^2)_6)_9$ state, probably with a large $(vf_{7/2}i_{13/2})_9$ admixture. In ^{149}Gd , with the third valence neutron placed in the $h_{9/2}$ orbit, an analogous $27/2^+$ state can be formed. Since the $27/2^+$ isomer in ^{149}Gd decays in a similar manner as the ^{148}Gd 9^- level we interpret it as the $vh_{9/2} \times 9^-$ configuration. Its excitation energy, 863 keV above the $(vh_{9/2}(f_{7/2}^2)_6)_{21/2}$ state, also supports this suggestion as the corresponding $(vf_{7/2}^2)_6$ to 9^- energy separation in ^{148}Gd is 884 keV. The $23/2^+$ level at 3,228 keV is assigned as $vh_{9/2} \times 7^-$.

In the decay of the 6 ns isomer we observe the $27/2^+ \rightarrow 21/2^-$ $E3$ transition, analogous to the $9^- \rightarrow 6^+$ $E3$ transition [6] in ^{148}Gd . The half life and the decay branching ratio give

$$B(E3, 27/2^+ \rightarrow 21/2^-) = 44 \pm 11 \text{ W.U.}$$

This result compares with the $B(E3)$ values measured in ^{148}Gd and ^{147}Gd , $55 \pm 6 \text{ W.U.}$ [6] and $44 \pm 6 \text{ W.U.}$ [1]. Thus all Gd $B(E3)$ values at $N > 82$ are larger than the $37 \pm 4 \text{ W.U.}$ measured [30] for the ^{146}Gd core.

The isomeric 160 keV $E2$ transition has a $B(E2)$ value of

$$B(E2, 27/2^+ \rightarrow 23/2^+) = 12 \pm 1 \text{ W.U.}$$

In our interpretation this γ -ray is essentially a $vf_{7/2}^2 6^+ \rightarrow 4^+$ transition, although other configurations are expected to contribute to the $27/2^+$ and $23/2^+$ levels. Analogous isomeric $E2$ transitions have been observed in a number of neighbouring nuclei, and have been analyzed to determine an approximate value for the neutron effective $E2$ transition

charge. For ^{149}Gd we obtain

$$e_{\text{eff}} = 4.0 \pm 0.2 e.$$

This should be compared to the value of $2.7 \pm 0.1 e$ extracted from the analogous $9^- \rightarrow 7^-$ transition [6] in ^{148}Gd , and is in agreement with the systematics [31] of neutron e_{eff} values found for other $N=84$ and $N=85$ nuclei.

4.4. The $vf_{7/2}^3 \times 3^-$ States

In Sect. 3 we discussed the $I^\pi = 13/2^+$ assignment for the 956 keV level. This $13/2^+$ state is in nice accord with the isotonic systematics; $13/2^+$ states at similar energies have been identified in ^{153}Er ($E_x = 971 \text{ keV}$) [28], ^{151}Dy (968 keV) [27], ^{147}Sm (1,031 keV) [23, 26], ^{145}Nd (1,112 keV) [24], and probably also in ^{143}Ce (1,221 keV) [25]. In the latter three cases these states are populated with $l=6$ in single neutron transfer which indicates that the $vi_{13/2}$ single-particle excitation contributes strongly to them.

It has recently been argued [3] that the 1.6 MeV ^{146}Gd core octupole state lies lower in energy than the unperturbed $vi_{13/2}$ single-particle excitation in the $N=83$ nucleus ^{147}Gd . This suggests that the 997 keV $13/2^+$ state in ^{147}Gd , and probably also the 956 keV $13/2^+$ level in ^{149}Gd , are predominantly $vf_{7/2}^3 \times 3^-$ excitations rather than $vi_{13/2}$ single particle states, although one expects the two configurations to be strongly admixed.

The present data support this $vf_{7/2}^3 \times 3^-$ interpretation for the 956 keV level in ^{149}Gd . If the $vi_{13/2}$ single-particle excitation were dominant one would expect to observe a $(vf_{7/2}^2)_0, 2, 4, 6$ multiplet on top of the $13/2^+$ level. In contrast, we find the characteristic $vf_{7/2}^3$ multiplet associated with the $13/2^+$ state, which further points to the prevalent octupole character for that level. In the present work we have found four members of the $vf_{7/2}^3 \times 3^-$ multiplet, with spins $11/2^+$, $13/2^+$, $17/2^+$, and $21/2^+$. In a very recent study [12] the 874 keV state has been assigned as $11/2^-$ and an associated level at 1,751 keV as $15/2^-$. If these levels are reassigned to positive parity the 1,751 keV state could well be the $((vf_{7/2}^2)_{9/2} \times 3^-)_{15/2}$ multiplet member in analogy to a similar $15/2^{(+)}$ level [25] at 1,762 keV in ^{147}Sm .

An apparent difference between the ground state $f_{7/2}^3$ multiplet and the $vf_{7/2}^3 \times 3^-$ multiplet is the much lower relative energy of the $(vf_{7/2}^3)_{5/2}$ multiplet member in the latter case. In general the large negative quadrupole moment in a $(j^3)_{j-1}$ configuration gives rise to a lowering of the energy through the quadrupole interaction. The interaction with the predo-

minant $(\pi d_{5/2}^1 h_{11/2})3^-$ octupole configuration will further lower this $5/2^-$ state, thus giving rise to the $11/2^+$ level at 874 keV in ^{149}Gd , 83 keV below the $13/2^+$ state. A similar lowering of the $(\nu f_{7/2}^3)_{5/2}$ energy has also been established in other $N=85$ nuclei. In ^{147}Sm [26] and ^{150}Tb [32] the $\nu f_{7/2}^3$ multiplet associated with the octupole excitation has the same level ordering with the $5/2$ member respectively 99 keV and 42 keV below the $7/2$ member, and the $(\pi h_{11/2}^1 (\nu f_{7/2}^3)_{5/2})25/2^-$ state in ^{151}Dy [27] lies 47 keV below the associated $27/2^-$ state.

4.5. Higher-Lying Positive-Parity States

The experiments have established a number of additional positive parity states above 3 MeV which might involve the $\nu i_{13/2}$ orbital. However, negative parity states of proton particle-hole character occur [6] at $E_x \geq 3$ MeV in the yrast line of ^{148}Gd , which makes characterization of positive parity levels in ^{149}Gd in this region rather uncertain and prevents configuration assignments for higher-lying states. The strongly populated $25/2^+$ state at 3,295 keV may be the $\nu i_{13/2} f_{7/2}^2$ state with maximum spin alignment which cannot mix with the $\nu f_{7/2}^3 \times 3^-$ multiplet. The energy of that state can in principle be calculated as

$$\begin{aligned} E_x((i_{13/2} 2 f_{7/2}^2)_{25/2}) \\ = E_x((f_{7/2}^2)_6) + 2 \times \Delta E((f_{7/2} i_{13/2})_{10,9}) \\ + E_x(i_{13/2}) + E_0 \end{aligned}$$

where in this case the mass parameter [18, 19] is

$$\begin{aligned} E_0 = -M(^{146}\text{Gd}) + M(^{147}\text{Gd}) + M(^{148}\text{Gd}) \\ - M(^{149}\text{Gd}) = -537 \text{ keV}. \end{aligned}$$

The first term is the excitation energy of the $(\nu f_{7/2}^2)_6^+$ state in ^{148}Gd . The $\nu f_{7/2} i_{13/2}$ residual interaction ΔE for $I=10,9$ is expected to be smaller than ~ 0.1 MeV and is neglected here. The third term is the unperturbed $\nu i_{13/2}$ single-particle energy. This energy is an important quantity for yrast level calculations in this region, but unfortunately it is not well known from the spectrum of ^{147}Gd . We therefore can estimate it from the above equation. The result

$$\varepsilon(i_{13/2}) - \varepsilon(f_{7/2}) = 2.0(1) \text{ MeV}$$

supports the earlier [3] contention that the $i_{13/2}$ single-neutron state lies higher than the 1.6 MeV octupole excitation of ^{146}Gd . It also agrees with a similar indirect estimate ($\varepsilon(i_{13/2}) \geq 2$ MeV) obtained [6] from the ^{148}Gd yrast level spectrum. The

± 0.1 MeV uncertainty in $\varepsilon(i_{13/2})$ derives from the neglect of the residual interaction only. It is difficult to estimate a more realistic uncertainty since as we have pointed out it is not quite clear whether the spherical shell model at $N=85$ can be applied in a quantitative manner.

The same considerations are valid for the $23/2^+$ member of the $\nu i_{13/2} f_{7/2}^2$ multiplet, which is also free of $\nu f_{7/2}^3 \times 3^-$ admixtures. The $23/2^+$ level at 3,085 keV could possibly be this excitation.

4.6. The Negative-Parity Levels at 2,058, 2,384, and 3,135 keV

For essentially all levels below 3 MeV shown in Fig. 4 it is possible to give reasonably firm structure interpretations as discussed in the preceding sections. The only exceptions are the very low-lying $17/2^-$ level at 2,058 keV mentioned in Sect. 4.2, and two additional negative parity states with $I=19/2$ and $23/2$ at 2,384 and 3,135 keV. We have previously argued that the $17/2^-$ state cannot be the expected second $17/2$ member of the $\nu h_{9/2} f_{7/2}^2$ multiplet. The same argument is valid for the 2,384 keV $19/2^-$ state, since the $(\nu h_{9/2} f_{7/2}^2)_{19,2}$ level should also lie higher than the $21/2^-$ multiplet member. It is difficult to form such $17/2^-$ or $19/2^-$ states at this low excitation energy from the three valence neutrons. On the other hand, the observed levels also lie too low to involve more complex particle-core excitations.

A possible interpretation for the 2,384 keV $19/2^-$ level is to attribute it to a $(3^- \times 3^-)6^+$ two-phonon octupole excitation built on the ground state. The $17/2^-$ and $23/2^-$ levels, accordingly, would correspond to the $5/2^-$ and $11/2^-$ members of the $\nu f_{7/2}^3$ multiplet. This interpretation is indicated on the level scheme of Fig. 4. The $19/2$ to $17/2$ energy separation is here as large as 326 keV. One would indeed expect an additional lowering of the $(\nu f_{7/2}^3)_{5/2}$ state in the case of two phonons, and when comparing the $5/2$ to $7/2$ energy separation in the three multiplets $\nu f_{7/2}^2$, $\nu f_{7/2}^2 \times 3^-$, and $\nu f_{7/2}^3 \times 3^- \times 3^-$ one notices as expected a regular behaviour for the energy lowering of the $5/2$ state.

In quite similar $(\alpha, x n)$ in-beam studies [26, 27] of the neighbouring $N=85$ isotones ^{151}Dy and ^{147}Sm no analogous low-lying negative parity levels are found. This is in accord with our interpretation of the ^{149}Gd states, since it is well known, from the even mass $N=82$ to 86 level systematics that the octupole excitation is lowest in Gd. Similarly, in the odd A nuclei with $N=83$ and $N=85$, the first $13/2^+$

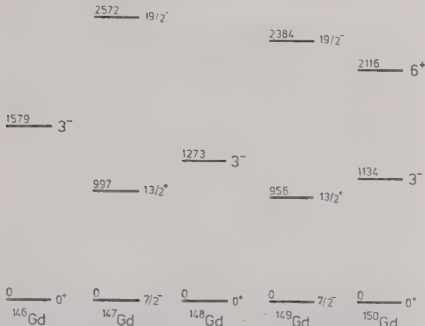


Fig. 6. Octupole states and tentative two-phonon octupole states in Gd nuclei with $N \geq 82$

excitation, which is of predominant $\nu f_{7/2} \times 3^-$ character, is also lowest in Gd.

Candidates for two-phonon octupole excitations exist also in other Gd isotopes. In the $N=83$ nucleus ^{147}Gd a $19/2^-$ level at 2,572 keV decays [1] through an $E3$ transition to the 997 keV $13/2^+$ level of mostly $[3] \nu f_{7/2} \times 3^-$ character. It has been argued [1] that this $19/2^-$ state has a large $\nu f_{7/2} \times 3^- \times 3^-$ component, since also in this case it is difficult to construct any other $I^\pi=19/2^-$ state at such a low excitation. An (α, n) study [33] of the $N=86$ nucleus ^{150}Gd has identified a second 6^+ level as low as 2.12 MeV which may have a significant $3^- \times 3^-$ amplitude. Also here, an analogous 6^+ state has not been found [34, 35] in the isotope ^{152}Dy which was studied in similar (α, xn) experiments. In Fig. 6 we show the energy systematics of octupole excitations in Gd nuclei, and we have also included the possible candidates for two-phonon octupole excitations. Of course at present these identifications are quite speculative, in particular as long as no $(3^-)^2 \rightarrow 3^- B(E3)$ transition rate has been measured. Unfortunately the complex level schemes of the nuclei with 84 and more neutrons make the observation of such an $E3$ transition quite unlikely. However, due to the low energy of the octupole excitation, the Gd nuclei with $N > 82$ should be particularly favourable for the observation of the two-phonon octupole states.

5. Conclusion

The present study has established the ^{149}Gd high-spin energy spectrum up to ~ 4 MeV excitation, and

we have interpreted the results in terms of the spherical shell model.

The measured level energies of the three neutron $f_{7/2}$ multiplet are not well reproduced from the $\nu f_{7/2}^3$ energies of ^{149}Gd assuming pure two-nucleon interactions. The deviations suggest that long-range contributions become increasingly important already at $N=85$, only three neutrons above $N=82$. Nevertheless, the observed level spacings qualitatively resemble those calculated for a $\nu f_{7/2}^3$ multiplet.

Observation of the characteristic multiplets arising from $f_{7/2}$ valence neutrons has proven quite valuable for determining configuration assignments in ^{149}Gd as well as in other $N=85$ nuclei [26, 27, 32, 28]. Thus, collective excitations, or predominantly proton states, are associated with the $\nu f_{7/2}^3$ multiplet, whereas a $\nu f_{7/2}^3$ multiplet is found in combination with e.g. the $h_{9/2}$ intrinsic excitation in the $N=85$ nuclei.

The $\nu f_{7/2}^3$ multiplet observed in combination with the $13/2^+$ state emphasizes the predominant octupole character of that state, and the analysis of highly lying positive parity levels suggests a ~ 2 MeV $\nu f_{7/2} \times \nu i_{13/2}$ single-particle energy separation. Somewhat speculatively, a low-lying $19/2^-$ level which cannot be interpreted as valence nucleon state is assigned as a two-phonon octupole excitation. Although at present this assignment cannot be proven it fits in well with the properties of octupole excitations in the Gd region.

First results on the high spin structure of ^{149}Gd came from measurements in 1972 at the Berkeley 88' cyclotron, and we are indebted to M.R. Maier, R.M. Diamond, F.S. Stephens, and R.K. Sheline who participated in these early experiments. We thank M. Ogawa and R. Broda for their expert help during the measurements at Jülich, and we warmly acknowledge valuable and productive discussions with O. Schult. This work has been supported by a travel grant from the Nordic Committee for Accelerator-based Research.

References

1. Kleinheinz, P., Broda, R., Daly, P.J., Lunardi, S., Ogawa, M., Blomqvist, J.: Z. Phys. A - Atoms and Nuclei **290**, 279 (1979)
2. Broda, R., Behar, M., Kleinheinz, P., Daly, P.J., Blomqvist, J.: Z. Phys. A - Atoms and Nuclei **293**, 135 (1979)
3. Daly, P.J., Kleinheinz, P., Broda, R., Lunardi, S., Backe, H., Blomqvist, J.: Z. Phys. A - Atoms and Nuclei **298**, 173 (1980)
4. Kleinheinz, P.: Proc. Symp. on High Spin Phenomena in Nuclei, Argonne, (1979), ANL/PHY-79-4, p. 125
5. Bergström, I.: Proc. XVI Int. Winter Meeting on Nuclear Physics, Bormio, (1978), Iori, I. (ed.) Vol. II, p. 636
6. Lunardi, S., Ogawa, M., Maier, M.R., Kleinheinz, P.: Proc. Symp. on High Spin Phenomena in Nuclei, Argonne, (1979), ANL/PHY-79-4, p. 393, and Inst. f. Kernphysik, KFA-Jülich, Annual Report 1979, p. 51
7. Kleinheinz, P., Stefanini, A.M., Maier, M.R., Sheline, R.K., Diamond, R.M., Stephens, F.S.: Nucl. Phys. A **283**, 189 (1977)

8. Toth, K.S., Newman, E., Bingham, C.R., Rainis, A.E., Schmidt-Ott, W.-D.: *Phys. Rev. C* **11**, 1370 (1975)
9. Holland, G.E.: *Nucl. Data Sheets* **19**, 337 (1976)
10. Jackson, S.V., Starner, J.W., Daniels, W.R., Bunker, M.E., Meyer, R.A.: *Phys. Rev. C* **18**, 1840 (1978)
11. Kleinheinz, P., Sheline, R.K., Maier, M.R., Diamond, R.M., Stephens, F.S.: *Phys. Rev. Lett.* **32**, 68 (1974)
12. Rakel, D., Funk, E., Mihelich, J.: *Univ. of Notre Dame, Annual Report 1979*, p. 45
13. Piiparinen, M., Pengo, R., Nagai, Y., Kleinheinz, P., Roy, N., Carlén, L., Ryde, H., Lindblad, Th., Johnson, A., Hjorth, S.A., Hammarén, E.: *Proc. Int. Conf. on Nuclear Behaviour at High Angular Momentum*, Strasbourg, p. 63 (1980), and *BAPS* **24**, 827 (1979)
14. Piiparinen, M., Pengo, R., Nagai, Y., Kleinheinz, P., Roy, N., Carlén, L., Ryde, H., Lindblad, Th., Johnson, A., Hjorth, S.A.: *Inst. f. Kernphysik, KFA-Jülich, Annual Report 1979*, p. 53, and *Research Institute of Physics, Stockholm, Annual Report 1979*, p. 93
15. Moll, E., Kankaleit, R.: *Nukleonik* **7**, 80 (1965)
16. Ekström, C., Ingelman, S., Olsmats, M., Wannberg, B.: *Phys. Scr.* **6**, 181 (1972)
17. de-Shalit, A., Talmi, I.: *Nuclear Shell Theory*. New York: Academic Press 1963
18. Wapstra, A.H., Bos, K.: *At. Data Nucl. Data Tables* **19**, 177 (1977)
19. Blomqvist, J., Kleinheinz, P., Broda, R., Daly, P.J.: *Z. Phys.* (to be published)
20. Bergström, I., Blomqvist, J., Fant, B., Herrlander, C.J., Lindén, C.G., Wikström, K.: *Proc. XII Winter Meeting on Nuclear Physics*, Villars, Switzerland, 1974
21. Wilson, J., Faber, S.R., Daly, P.J., Ahmad, I., Borggreen, J., Chowdhury, P., Khoo, T.L., Lawson, R.D., Smither, R.K., Blomqvist, J.: *Z. Phys. A - Atoms and Nuclei* **296**, 185 (1980)
22. Toth, K.S., Bingham, C.R., Carter, H.K., Sousa, D.C., Zolnowski, D.R.: *BAPS* **23**, 627 (1978)
23. Harmatz, B., Ewbank, W.B.: *Nucl. Data Sheets* **25**, 113 (1978)
Rekstad, J.B., Løvheiden, G., Lien, J.R., El-Kazzaz, S., Ellegaard, C., Bjerregaard, J.H., Knudsen, P., Kleinheinz, P.: *Nucl. Phys. A* **348**, 93 (1980)
24. Hillis, D.L., Bingham, C.R., McClude, D.A., Kendrick, N.S., Jr., Hill, J.C., Raman, S., Ball, J.B., Harvey, J.A.: *Phys. Rev. C* **12**, 260 (1975)
Løvheiden, G., Lien, J.R., El-Kazzaz, S., Rekstad, J., Ellegaard, C., Bjerregaard, J.H., Knudsen, P., Kleinheinz, P.: *Nucl. Phys. A* **339**, 477 (1980)
25. Lessard, L., Gales, S., Foster, J.R., Jr.: *Phys. Rev. C* **6**, 517 (1972)
26. Piiparinen, M., Nagai, Y., Styczen, J., Kleinheinz, P.: *Proc. Int. Conf. on Nuclear Behaviour at High Angular Momentum*, Strasbourg, p. 53 (1980), and *Inst. f. Kernphysik, KFA-Jülich, Annual Report 1979*, p. 55
27. Piiparinen, M., Lunardi, S., Kleinheinz, P., Backe, H., Blomqvist, J.: *Z. Physik A - Atoms and Nuclei* **290**, 337 (1979)
28. Carlén, L., Jonsson, S., Lyttkens, J., Ryde, H., Strömberg, S., Hagemann, G.B., Herskind, B.: *Proc. Int. Conf. on Nuclear Interactions*, Canberra, Springer, 1978, p. 417, and *Dept. of Physics, Univ. of Lund, Annual Report 1979*, p. 17
Horn, D., Young, G.R., Lister, C.J., Baktash, C.: *Proc. Int. Conf. on Nuclear Behaviour at High Angular Momentum*, Strasbourg, p. 81 (1980), and *Phys. Rev. C* **23**, 1047 (1981)
29. Newman, E., Toth, K.S., Hensley, D.C., Schmidt-Ott, W.-D.: *Phys. Rev. C* **9**, 674 (1974)
30. Kleinheinz, P., Ogawa, M., Broda, R., Daly, P.J., Haenni, D., Beuscher, H., Kleinrahm, A.: *Z. Phys. A - Atoms and Nuclei* **286**, 27 (1978)
31. Lunardi, S., Ogawa, M., Backe, H., Piiparinen, M., Nagai, Y., Kleinheinz, P.: *Proc. Symp. on High Spin Phenomena in Nuclei*, Argonne, (1979), *ANL-PHY-79-4*, p. 403, and *Inst. f. Kernphysik, KFA-Jülich, Annual Report 1979*, p. 52
Lunardi, S.: *Proc. XVIII Winter School on Nuclear Structure*, Bielsko-Biala (1980)
32. Broda, R., Ogawa, M., Kleinheinz, P., Sheline, R.K., Richter, L.: *Proc. Symp. on High Spin Phenomena in Nuclei*, Argonne, (1979), *ANL-PHY-79-4*, p. 401, and *Inst. f. Kernphysik, KFA-Jülich, Annual Report 1978*, p. 29
33. Haenni, D.R., Sugihara, T.T.: *Phys. Rev. C* **16**, 120 (1977)
34. Jansen, J.F.W., de Voigt, M.J.A., Sujkowski, Z., Chmielewska, D.: *Nucl. Phys. A* **321**, 365 (1979)
35. Nagai, Y., Styczen, J., Piiparinen, M., Kleinheinz, P.: *Proc. Int. Conf. on Nuclear Physics*, Berkeley, p. 304 (1980)

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Search for High-Spin Isomers in $^{150}\text{Dy}^*$

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Abstract

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A search for yrast traps in ^{150}Dy has been made by studying the γ -ray decay following the $^{144}\text{Nd} (^{12}\text{C}, 6n)$ ^{150}Dy and $^{146}\text{Nd} (^{12}\text{C}, 8n)$ reactions. Although an average value of about 30 units of angular momentum is imparted to the final nucleus using these reactions, no evidence is found for the existence of isomers with half-lives longer than 10 ns.

1. Introduction

The properties of nuclear structure at high angular momenta are presently very much discussed. One of the intriguing problems in this field concerns the existence of high-spin isomeric states, i.e., so called yrast traps, that may appear when the single-particle potential becomes axially symmetric with respect to the spin direction [1]. Within this picture the levels in the yrast region do not form rotational bands, but rather appear as individual particle states. In such a scheme the level energy is not necessarily a monotonically increasing function of spin. Furthermore, the transition probabilities are essentially those of the single-particle model and are occasionally strongly retarded. For these reasons, levels having measurable half-lives may very well occur.

Recently, a systematic search for delayed cascades of γ -rays with high multiplicity was reported [2, 3]. Lifetimes from a few ns to several hundred nanoseconds were observed in the region $64 \leq Z \leq 71$ and $82 \leq N \leq 88$, although the spin and the decay pattern of the isomers, as well as the exact mass number, were not determined. However, it is interesting to note that recent theoretical calculations [4, 5] indicate that there are good reasons to expect the occurrence of yrast traps in the aforementioned region.

The nucleus $^{150}\text{Dy}_{84}$ is found in the middle of this region and has two neutrons outside the closed $N = 82$ shell and two protons outside the essentially inert $Z = 64$ core. These four particles may form states with spin-values ranging from zero to 22, which is the highest spin that may be obtained from the $(\nu_{13/2})^2 (\pi h_{11/2})^2$ configuration. Formation of other states of equal and higher values of spin must involve excitation of the core and hence at least an additional excitation energy of about 1.5 MeV. The structure of the $I^\pi = 22^+$ level is characterised as “Maximization of Overlap of Nucleonic wave functions by

means of Alignment of angular momentum” (MONA) [6]. This state should therefore have a good chance of becoming an yrast trap.

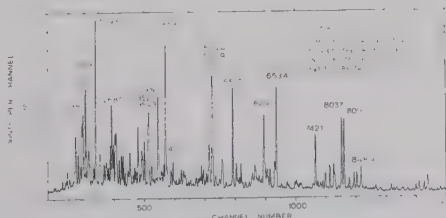
In view of the arguments above, the $(^{12}\text{C}, xn)$ reactions with $x = 6$ and 8 were used in a search for high-spin isomeric states in ^{150}Dy .

2. Experimental procedure and results

In the present experiment, beams of ^{12}C -ions from the Stockholm 225 cm cyclotron were used to bombard thin ($\approx 3 \text{ mg cm}^{-2}$) foils of ^{144}Nd and ^{146}Nd (enrichment $\approx 98\%$). The energies of the projectiles were chosen to be 112 MeV and 118 MeV, respectively, in order to produce the final nucleus ^{150}Dy by means of the $(^{12}\text{C}, 6n)$ and $(^{12}\text{C}, 8n)$ reactions.

In-beam γ -ray spectroscopy techniques were applied using a Ge(Li)–NaI(Tl) Compton suppression arrangement [7], in order to obtain a high peak to background ratio. Singles spectra, as well as spectra correlated in time with respect to the naturally pulsed cyclotron beam ($\nu \approx 8 \text{ MHz}$), were recorded. An additional condition was introduced by requiring $\gamma\gamma$ -coincidences between the Ge(Li) detector and a $12.5 \times 12.5 \text{ cm}$ NaI(Tl) crystal in order to suppress low multiplicity transitions due to radioactive decay. Such a spectrum recorded during the bombardment of the ^{144}Nd target with 112 MeV ^{12}C -ions is shown in Fig. 1. By comparing this spectrum with spectra obtained at other bombarding energies and spectra obtained from the $(^{12}\text{C}, 8n)$ ^{150}Dy reaction, a number of lines are assigned to ^{150}Dy as shown in Fig. 1. However, in the time correlated spectra, there is no evidence for observing delayed transitions with half-lives longer than about 10 ns. Thus the data show no indication that a high-spin isomer is populated in this reaction.

In order to gain further insight into the level structure of



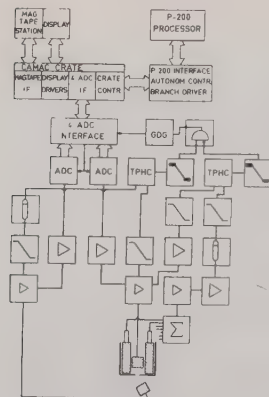


Fig. 2. Schematic drawing of the electronics used in connection with the Ge(Li)-Ge(Li) $\gamma\gamma$ -coincidence experiment with one Compton suppressed channel.

^{150}Dy , a two-dimensional $\gamma\gamma$ -coincidence experiment was performed using the Compton-suppression γ -ray spectrometer and an additional Ge(Li) detector. A block diagram showing the complete electronic set-up is shown in Fig. 2. Due to the low efficiency in the Compton suppressed channel the typical coincidence counting rate was generally less than 20 events per second. A total number of about 200 000 events were collected in the experiment. The analysis was performed by setting gates on peaks and suitably selected background intervals in the spectrum obtained from the detector having no Compton suppression annulus. Some of the results of this experiment are shown in Fig. 3. In spite of the fact that the total number of events is very small, the low background in the anti-Compton channel implies coincidence spectra having equal or better quality than is normally obtained with ($^{12}\text{C}, \alpha n$) reactions.

The most remarkable property of these coincidence spectra is the unusually large number of transitions of roughly the

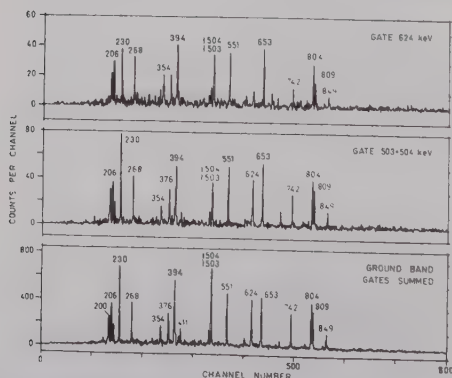


Fig. 3. Examples of coincidence spectra obtained with the set-up shown in Fig. 2. A total number of 200 000 coincidence events were collected during the bombardment of a ^{144}Nd target with ^{12}C ions.

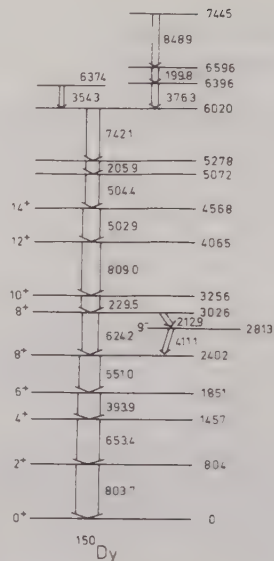


Fig. 4. Proposed level scheme for ^{150}Dy . Spin and parity assignments are taken from the work of Lunardi *et al.* [8].

same strength observed in each spectrum. In fact, it appears as if 14 transitions of about comparable strength are in coincidence with each other. Under such conditions, it is difficult to order these transitions by using arguments based on γ -ray intensities. The construction of the level scheme (shown in Fig. 4) is therefore based to a large extent on the recent findings of Lunardi *et al.* [8], who populated states in ^{150}Dy by means of an ($\alpha, \alpha n$) reaction. In their work, the transition intensities decrease monotonically with spin or excitation energy up to a level at 6.02 MeV. In our work, there is evidence for at least four more transitions feeding the 6.02 MeV level. Three of these transitions form a coincidence cascade, but due to the very similar intensities of these transitions it is not possible to order the transitions in an unambiguous sequence.

In the work of Lunardi *et al.* [8], spin and parity are assigned to levels up to 4.568 MeV ($I^\pi = 14^+$). In the present work, a cascade of six transitions is observed on top of this 14^+ level. Since the calculated average angular momentum in the present reaction is about 30 $\hbar$, one may suggest that this cascade connects states having monotonically increasing values of spin. In particular, it seems quite reasonable that a level with $I^\pi = 22^+$ is depopulated by dipole and/or quadrupole transition within this cascade.

3. Discussion

The residual interaction in the $(\nu i_{3/2})^2 (\pi h_{11/2})^2$ configuration is expected to force the $I^\pi = 22^+$ level below the members of this configuration with spin and parity 21^+ and 20^+ [9]. The decay is therefore expected to proceed by an M2 transition to the 20^+ level of the configuration $(\nu i_{3/2})^2 (\pi h_{11/2})^2$. This transition should certainly be delayed with a half-life longer

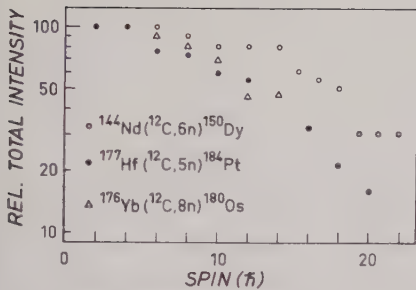


Fig. 5. Transition intensity versus spin for the $^{144}\text{Nd} (^{12}\text{C}, 6n) ^{150}\text{Dy}$ reaction. Two other $(^{12}\text{C}, xn)$ reactions are shown for comparison. For the case of ^{150}Dy , the highest spin observed is assumed to be 22 and the levels between the state having this spin value and the state with $I^\pi = 14^+$ are equally spaced with respect to spin.

than 10 ns. Hence it should be measurable in the present experiment. The reason for the non-isomerism must then be explained by the fact that the 21^- level of the $(\nu_{13/2} \nu_{h_{9/2}}) (\pi h_{11/2})^2$ configuration is forced down below the 22^+ level due to the strong $i_{13/2} - h_{9/2}$ interaction. This means that the decay now can take place by means of an E1 transition.

Turning to the intensities of the observed transitions, it may be concluded that the levels of high spin receive a large fraction of the total intensity. This is seen in Fig. 5, where the transition intensity is plotted as a function of spin for the $^{144}\text{Nd} (^{12}\text{C}, 6n) ^{150}\text{Dy}$ reaction and for two other $(^{12}\text{C}, xn)$ reactions. As seen in this figure, the transition intensity for a given spin is much larger in ^{150}Dy . In fact, for the same relative intensity, the spin value is up to 4 units higher in ^{150}Dy than in the two other nucleides.

There is another way of looking at these data, namely to form the sum $\sum L_\gamma(I \rightarrow I-2)/L_\gamma(2 \rightarrow 0)$. This quantity is the

part of the total multiplicity of the γ -rays, which is due to the discrete, or at least observed, transitions. In ^{150}Dy , this quantity makes up for about 50% of the total multiplicity, whereas in the two other reactions studied, the same figure generally is less than 30%.

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References

- [1] Bohr, A. and Mottelson, B. R., *Physica Scripta* **10A**, 13 (1974) and *Nuclear Structure*, Benjamin, New York, N.Y., 1975, Vol. 2.
- [2] Pedersen, J., Back, B. B., Bernthal, F. M., Björnholm, S., Borggreen, J., Christensen, O., Folkman, F., Herskind, B., Khoo, T. L., Neiman, M., Pühlhofer, F. and Sletten, G., *Int. Symp. on High-Spin States and Nucl. Structure*, Dresden, 1977, p. 98.
- [3] Pedersen, J., Back, B. B., Bernthal, F. M., Björnholm, S., Borggreen, J., Christensen, O., Folkman, F., Herskind, B., Khoo, T. L., Neiman, M., Pühlhofer, F. and Sletten, G. (to be published).
- [4] Andersson, G., Larsson, S. E., Leander, G., Möller, P., Nilsson, S. G., Ragnarsson, I., Aberg, S., Bengtsson, R., Dudek, J., Nerlo-Pomorska, B., Pomorski, W. and Szymański, Z., *Nucl. Phys. A* **268**, 205 (1976).
- [5] Døssing, T., Neergård, K. and Hsi-Chen Chang (to be published).
- [6] Faessler, A., Płoszajczak, M. and Sandhya Devi, K. R., *Phys. Rev. Lett.* **36**, 1028 (1976).
- [7] Johnson, T. and Lindblad, Th., *Research Institute of Physics, Annual Report 1975*, p. 172; Lindblad, Th., *Nucleonica* **22** (1976) and to be published.
- [8] Lunardi, S., Ogawa, M., Maier, M. R. and Kleinheinz, P., *IKP-KFA Jülich, Annual Report 1976*, p. 31 and *Int. Symp. on High-spin States and Nucl. Structure*, Dresden, 1977, p. 28.
- [9] Blomqvist, J., *Research Institute of Physics* (private communication).

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HIGH SPIN STATES AND YRAST ISOMERISM IN ^{153}Er

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ABSTRACT

Energy levels in ^{153}Er have been populated in the reaction $^{144}\text{Sm}(^{12}\text{C}, 3n)^{153}\text{Er}$. Isotopically enriched targets were bombarded with 53-65 MeV ^{12}C ions and the emitted γ -ray and conversion electron spectra were investigated. From studies of excitation functions, γ - γ coincidences, γ -ray multiplicities, delayed γ -radiation and angular distributions, the level scheme of ^{153}Er has been constructed. The properties of the energy levels are discussed and compared with the results of calculations with a deformed shell model. The remarkable similarities and some important discrepancies of the level structure, when compared with adjacent $N = 85$ nuclides, are emphasized.

NUCLEAR REACTION $^{144}\text{Sm}(^{12}\text{C}, 3n)^{153}\text{Er}$, $E = 53\text{--}65$ MeV; measured E_γ , $I_\gamma(E)$, $I_\gamma(t)$, $I_\gamma(0)$, mean values and standard deviations of γ -ray multiplicities, E_e , I_e . ^{153}Er deduced levels, J , π , $T_{1/2}$. Enriched targets, Ge (Li), Ge, NaI(Tl) detectors, Compton suppression, mini-orange electron spectrometer with Si(Li) detector.

1. Introduction

The level structure of light rare-earth nuclei with $Z \geq 64$ and $N > 82$ has recently been discussed ⁽¹⁾ in terms of the independent-particle model with the semi-closed shell nucleus ^{146}Gd acting as a core. The properties of high-spin states along the yrast line were early discussed ^(2,3,4) and the predicted existence of isomeric states in this region was experimentally confirmed in a survey work ⁽⁵⁾. The response of the core to the polarizing effect of a successively increasing number of valence nucleons is an intriguing question. It has thus been pointed out ⁽⁶⁾ that high spin isomers seem suddenly to disappear for $N > 87$. The abrupt transition to prolate shapes of the nuclear ground states when going from $N = 88$ to $N = 90$ has been well known for a long time.

A series of even- Z isotones having $N = 85$ has been studied by many groups. The nuclide ^{145}Nd with $Z = 60$ has been investigated by Hammarén *et al.* ⁽⁷⁾, ^{147}Sm by Kownacki *et al.* ⁽⁸⁾ and by Piiparinen *et al.* ⁽⁹⁾, ^{149}Gd and ^{151}Dy by Piiparinen *et al.* ^(10, 11). In the present paper the properties of the nucleus ^{153}Er with $Z = 68$ are discussed. When this investigation started the level structure of this nuclide was completely unknown. The first results establishing the decay of a 373 ns isomer at 2751 keV in ^{153}Er are reported elsewhere ⁽¹²⁾. Several groups ⁽¹³⁻¹⁶⁾ have registered the existence of an additional isomeric state at around 5 MeV. Recently a detailed spectroscopic study of high spin single particle states in ^{153}Er has been performed by Horn *et al.* ⁽¹⁶⁾ using various nuclear reactions. Their results are partly complementary to the present ones as higher projectile energies were used.

2. Experiments and results

Energy levels in ^{153}Er were populated in the $^{144}\text{Sm}(^{12}\text{C}, 3n)^{153}\text{Er}$ reaction. Isotopically enriched (>95%), 1-4 mg/cm² thick ^{144}Sm targets mounted onto lead backings were bombarded with 53-65 MeV ^{12}C ions from the NBI Tandem Accelerator. Gamma-ray spectra were analysed using the computer code CARATE ⁽¹⁷⁾.

When the present investigations were started, no transitions in ^{153}Er were known. Gamma-rays due to transitions in this nucleus were distinguished from those in ^{154}Er , the other dominating product nucleus, with a sum-spectrometer ⁽¹⁸⁾ set-up. This consisted of a large cylindrical NaI(Tl) crystal supplemented by two Ge(Li) counters placed at 90° to each other. The solid angle subtended by the NaI(Tl) detector was 70% of 4π, giving a high efficiency for the total γ-radiation to be detected.

In the $^{144}\text{Sm}(^{12}\text{C}, 3n)^{153}\text{Er}$ reaction, there is less energy available for γ-radiation after the evaporation of three neutrons than is the case for the 2n channel. Consequently in the low-energy part of the spectrum recorded by the NaI(Tl) detector transitions in ^{153}Er are much stronger than in the high energy part, which is dominated by transitions in ^{154}Er . The γ-ray spectra obtained with one of the Ge(Li)-detectors in coincidence with the low-energy and high-energy parts of the sum spectrum, respectively, are compared in fig. 1. The ratio of the γ-ray intensities in the two spectra is an order of magnitude larger for transitions in ^{153}Er than for transitions in ^{154}Er . The large peaks not belonging to ^{153}Er , that are visible only in the upper spectrum, are due to radioactive background.

A further support for the isotopic assignment of the γ -rays comes from the study of their excitation functions using ^{12}C beams of $E=53.0\text{--}64.5$ MeV. Two classes of strong transitions were easily identified, one with a yield maximum at around $E=60$ MeV, the other with monotonously increasing yield, assigned to ^{154}Er and ^{153}Er , respectively. Furthermore, these excitation functions were used for obtaining information about the γ -ray cascades in ^{153}Er nuclei as is demonstrated in fig. 2, where the γ -ray intensities are normalized to that of the 299.4 keV transition to the ground state. If compared to the level scheme for ^{153}Er , as presented in sect. 3, it is clear that the five transitions associated with the decay of the isomer at 2751 keV get more intensity as the bombarding energy increases. On the other hand the transitions associated with the ground state band and the positive parity band decrease in relative intensity for higher beam energies. Finally, the intensities of the transitions associated with the cascade by-passing the 2751 keV isomer show a very steep increasing tendency. These observations are in agreement with the findings of Horn *et al.*⁽¹⁶⁾, who used a higher bombarding energy and therefore observed hardly any population of the ground state band or of the positive parity band.

Integrated relative intensities were obtained from an angular distribution measurement at a bombarding energy of 62.3 MeV, described later in this section. The relative cross sections for the strongest reaction channels observed are about 46% for ^{153}Er , about 37% for ^{154}Er , about 8% for ^{150}Dy and less than 9% for ^{153}Ho , as measured from the transitions to the ground states.

The average multiplicities $\langle M \rangle$ of the γ -rays were studied as a function of the bombarding energy. One Ge(Li) detector and nine NaI(Tl) counters, compactly mounted (as described in ref. ⁽¹⁹⁾) in the upper hemisphere around the target, were used for the detection of the γ -radiation. Singles γ -ray spectra from the Ge(Li) counter as well as coincidence events between the Ge(Li) detector and one or more of the NaI(Tl) detectors were recorded. The average multiplicity $\langle M \rangle$ and the standard deviation σ of the multiplicity distribution were then deduced for the γ -rays from these data according to the procedure described by Andersen *et al.* ⁽¹⁹⁾. In fig. 3 the average multiplicities are shown for members of the isomeric cascade and a few other transitions in ^{153}Er , at various bombarding energies, together with the standard deviations for the isomeric transitions at 64.5 MeV.

It may be concluded from these results that the members of the cascade deexciting the isomer all show a weakly increasing multiplicity around 7, except for the 712.0 keV γ -ray, which shows a lower multiplicity of between 5 and 6, independent of the bombarding energy. Also the standard deviation of the multiplicity distribution is much smaller ($\sigma=1.5$) for the 712.0 keV γ -ray than for the other members of the cascade ($\sigma=3-4$). These results are consistent with the interpretation of the 712.0 keV γ -ray as being due to an isomeric transition on top of a cascade of altogether five members. The larger values for these other members of the cascade of both the multiplicity and the standard deviation are then due to the side feeding, mainly through the 910.0 keV transition, which by itself - quite naturally - shows even larger values for the multiplicity. These conclusions are also

in agreement with the results reported in refs.⁽¹⁵⁾. They found an average multiplicity of 5.6 ± 1.0 for the delayed cascade and of 8.6 ± 1.0 for the by-passing cascade.

A search for delayed γ -rays and precursors was made by chopping the ^{12}C beam into 600 ns long pulses with a frequency of 1 MHz. Conventional delayed coincidence techniques were applied, using one intrinsic Ge and one Ge(Li) detector for energy measurements together with two NaI(Tl) crystals for timing requirement. In addition to the γ -rays from the known isomeric state in ^{154}Er with a half-life of 40 ns⁽²⁰⁾, five delayed γ -rays with a common half-life of 373 ± 9 ns were recorded. Cf. fig. 4. It should be noted here that the ratios between the prompt and delayed component for these various time distributions also indicate the ordering of the transitions within the cascade. Particularly the absence of a prompt component for the 712.0 keV γ -ray suggests that the corresponding transition de-excites the isomeric state itself*. No delayed γ -rays coming from the isomer reported at around 5 MeV (13-16) were observed. The intensity of the γ -rays connecting levels above 4.5 MeV is, however, too small for them to be detected in our pulsed beam experiment. In the spectra showing transi-

* It should be noted that Horn *et al.*⁽¹⁶⁾ suggest an isomeric transition of 7.5 keV above the 2751 keV level, based on their observation of a prompt component in the 712.0 keV transition together with energy balance calculations.

tions feeding the populated isomer, three γ -rays were assigned to ^{153}Er , as will be discussed in section 3.

In order to establish the multipolarity of the transitions, the angular distribution of the singles γ -ray spectrum was measured with a Ge(Li) detector at five different angles between $+58^\circ$ and $+148^\circ$ relative to the beam and at the same time with a second Ge(Li) detector in a Compton suppression set-up at angles between 0° and -90° . A third stationary Ge(Li) detector placed underneath the target served as a monitor. A radioactive source, ^{152}Eu , placed in the target position was used for efficiency calibration of the detectors at the various angles. The measurement was made at a bombarding energy of 62.3 MeV. The peak intensities, normalized to the monitor yields and corrected for the variation of the detection efficiency, were then fitted to the expression $W(\theta) = A_0 + A_2P_2(\cos \theta) + A_4P_4(\cos \theta)$. The two sets of data were in excellent agreement and the values of A_2/A_0 and A_4/A_0 measured with the single Ge(Li) detector are given in table 1 together with the integrated relative intensities.

It is interesting to note here that the 712.0 keV γ -radiation comes out isotropic, which would be expected for an isomeric transition. The other members of the delayed cascade show angular distributions characteristic of attenuated quadrupole radiation, with the exception of the 299.4 keV transition, which is of dipole character.

As the properties of the 712.0 keV transition are crucial, a measurement of the conversion coefficients for the transitions in this energy range was performed. The conversion electron spectrum was obtained by a mini-orange electron spectrometer with a cooled Si(Li) detector, and the γ -ray spectrum was simultaneously measured by a Ge(Li) detector. Both detectors were in coincidence with a filter consisting of 6 NaI(Tl) detectors. The experiment was done at a bombarding energy of 61.0 MeV. The conversion coefficients were normalized to the theoretical K-conversion coefficients⁽²¹⁾ for the known E2 transitions in ^{154}Er with energies of 601 and 625 keV. The results are presented in fig. 5. The 588.1, 754.4, 765.6 and 811.5 keV transitions are all clearly E2 transitions, in agreement with the conclusions drawn from the angular distribution measurements. From this measurement of the conversion coefficients it may be concluded that the 712.0 keV transition is either of E3 or M1 character*.

The results of γ - γ coincidence experiments are of decisive importance for the establishment of the level scheme. Two independent measurements were performed. In the first set-up four Ge(Li) detectors were placed at $\theta=0^\circ$, 55° , 90° and 90° . Using a ^{12}C beam of 63.0 MeV, coincident events between the detector mounted at 0° and any one of the remaining three detectors were recorded on magnetic

* It can not be fully excluded that the 712.0 keV transition is an E1 transition with a (40%) M2 admixture. However, this requires an extreme retardation of the E1 strength, which seems very unlikely.

tapes. Spectra from the 0^0 detector were afterwards constructed by setting gates on photo-peaks and appropriate background in the other detectors. The sorted spectra were added after background subtraction. The result of these analyses for transitions assigned to ^{153}Er are presented in table 2 and some particularly interesting coincidence spectra are displayed in figs. 6 and 7.

Another coincidence experiment at a bombarding energy of 65.0 MeV using 5 Ge(Li) detectors in Compton-suppression shields supplied no additional information.

3. The level scheme of ^{153}Er

The experimental information discussed above formed the basis for the construction of the level scheme, shown in fig. 8. Spin and parity of the ground state of ^{153}Er have not been measured. In conformity with adjacent $N=85$ even- Z nuclei, we make the assumption $J^\pi=7/2^-$. Spin and parity assignments are then based on the angular distribution and conversion coefficient results on the assumption of stretched cascades and on systematics as discussed in section 4.

The ordering of most of the transitions was deduced from the singles γ -ray intensities (cf. fig. 2). An additional check has been made by investigating the changes of the relative intensities of the γ -rays in the coincidence spectra obtained with gates set for the various members of the cascades. The

placement of the 363.1 keV and 653.2 keV transitions was determined mainly from the coincidence data due to contaminating γ -rays in ^{153}Ho and ^{150}Dy , respectively, in the singles spectra.

A 284.7 keV γ -ray is undoubtedly in coincidence with all the transitions below the 4477.0 keV level in the cascade shown to the left in fig. 8. However, it also belongs to the cascade above the isomeric level, most probably feeding the 4494.3 keV level. If this was a single γ -ray the only way to explain its coincidence with the left cascade below 4477.0 keV would be a connecting transition of 17.3 keV. From coincidence data, we can conclude that most of the intensity of the 284.7 keV peak feeds into the cascade by-passing the isomer. It is very unlikely that the 17.3 keV transition would feed most of the intensity into the left cascade, because of the expected branching ratio of the 17.3 keV and the 292.5 keV transitions depopulating the 4494.3 keV level. Therefore there are most probably two transitions with almost the same energy.

A very weak 787.1 keV γ -ray, observed for some of the gates in the coincidence spectra, most probably belongs to the decay scheme of ^{153}Er , but its position could not be determined.

The existence of a strong delayed γ -ray cascade of five members depopulating a state at 2751 keV was early established (12).

There are many reasons for suggesting the 712.0 keV transition at the top of the cascade to be due to an isomeric transition: the absence of a prompt component in its time distribution, the

isotropic angular distribution and the conversion coefficient suggesting an E3 character for the transition, in analogy with ^{149}Gd . The conversion coefficient is also compatible with an M1 transition. In that case, the long half life would be difficult to understand, unless there is a low-energy isomeric transition, preceding the M1 transition. This possibility, which cannot be excluded, will be further discussed in section 4. The present data are, however, consistent without assuming such a close-lying doublet.

A ground state band and a most probably positive parity band, seen up to spin 25/2, are fairly strongly populated at the present bombarding energies but hardly seen in experiments using higher energies ⁽¹⁶⁾. The angular distribution of the 205.1 keV transition connecting these two bands has dipole character.

A well-developed band feeding into the isomeric cascade at 2039.2 keV and thus by-passing the isomeric state, takes us up to a level at 5182.5 keV which has actually been tentatively suggested ⁽¹⁶⁾ to be an isomer with a half-life of 270 ns.

The delayed-coincidence experiment gave spectra showing the precursors. Besides transitions feeding the 40 ns isomer in ^{154}Er , three γ -rays of energies 194.3, 692.8 and 757.8 keV were seen. Traces of the 194.3 and 757.8 keV transition are also seen in coincidence spectra with gates on members of the isomeric cascade. We therefore conclude that the 194.3 and 757.8 keV transitions most probably feed into the isomeric state. The 757.8 keV transition is at the bottom of a cascade of which four members are observed. Two very weak lines at 429 and 659.3 keV are

observed in coincidence with the 194.3 keV transition, but it could not be determined whether they are in cascade or both feeding into the 2945.5 keV level. Therefore they were not included in the decay scheme.

4. Discussion

Some features of the $N=85$, even- Z isotones are remarkably similar, as illustrated in fig. 9. However, there are also important differences. This situation most probably reflects the interplay between the single particle character of these neutron-deficient rare-earth nuclei with $A \approx 150$ as discussed in ref. (1) and the increasing importance of the collective properties (3) as protons are added to or removed from the $Z=64$ semi-closed shell. In the following we restrict ourselves to a discussion of the isotones with $Z \geq 64$.

Calculations with the deformed shell model (3) have been performed. The potential energy surface is found to be very shallow for this and neighbouring nuclei with a preference towards an oblate shape (22). In the low spin region the minimum is close to a spherical shape with $\epsilon_2 \approx -0.1$, but as the spin increases the deformation seems to increase somewhat, although the potential energy surface is still quite shallow.

In the spherical shell model the ground state of ^{153}Er has the configuration $\nu(f_{7/2})^3$ and spin and parity $7/2^-$. This assignment is supported by the very striking resemblance (cf. fig. 9) between the level structures at low energy of the neighbouring

even- Z , $N = 85$ isotones which have $J^\pi = 7/2^-$ for their ground states⁽²³⁾.

The $11/2^-$ and $15/2^-$ members of the $(f_{7/2})^3$ multiplet are observed in the present experiment at energies that deviate from the corresponding ones in ^{151}Dy and ^{149}Gd by only a few percent. Other members of this multiplet are not observed here.

A $13/2$ state is found at 970.7 keV in ^{153}Er which is identified with the $13/2^+$ state at almost the same energy in the isotones ^{151}Dy and ^{149}Gd . Furthermore, the E2 transitions feeding the $13/2^+$ state have the same energies to within a few percent in the three isotones, constituting a multiplet which has been interpreted⁽¹⁰⁾ in the case of ^{149}Gd as predominantly $(f_{7/2})^3 x 3^-$ excitations, although strongly mixed with $(f_{7/2})^2 i_{13/2}$ single particle states. The maximum spin of the $(f_{7/2})^3 x 3^-$ multiplet is $21/2$. The $25/2$ state at 2908.5 keV may then be interpreted as a more pure $(f_{7/2})^2 i_{13/2}$ state with maximum spin alignment. The energies of the corresponding states in the two other isotones are here different. The $25/2$ to $21/2$ transition energies decrease considerably as the number of proton pairs increases.

A crucial point is the relative position of the deformed $h_{9/2}$ and $f_{7/2}$ neutron levels. In the spherical regime the j -shells are degenerate and $f_{7/2}$ lies below $h_{9/2}$. For a deformed configuration the shells are split, and, in the oblate case, the substates of maximum K -quantum number come lowest. The $f_{7/2}$ shell would in that case be filled with three particles to form the ground state of

^{153}Er , two particles with $K=7/2$ and one particle with $K=5/2$ whereas the close-lying $h_{9/2}$ orbital is empty. At increasing oblate deformation the $(h_{9/2}, K=9/2)$ state may even be found below the $(f_{7/2}, K=5/2)$ state. Assuming that the ground state is $7/2^-$, a $9/2$ state is found in ^{153}Er at 299.4 keV and interpreted as the lowest member of a $\nu(f_{7/2})^2 h_{9/2}$ multiplet. It is interesting to note that the corresponding state appears at lower energies as the proton number is increased over the $Z=64$ shell (cf. fig. 9). This fact may in itself be an indication of a slightly oblate shape of the ground state of ^{153}Er .

The $9/2, 13/2, 17/2, 21/2$ members of the $(f_{7/2})^2 h_{9/2}$ multiplet are found with an energy spacing, that quite clearly carries a remembrance of the $0^+, 2^+, 4^+$ and 6^+ sequence in the doubly even neighbouring nucleus ^{152}Er . This observation supports the interpretation of the one valence neutron being raised into the $h_{9/2}$ orbital and with the remaining $f_{7/2}$ neutron pair being excited through the sequence known from the doubly-even nucleus. Very similar energy spacings within this multiplet are also observed for the other isotones.

Isomeric states are observed in adjacent $N=85$ nuclides. Thus in ^{149}Gd a 6.0 ns isomer is reported ⁽¹⁰⁾ at 3387 keV while in ^{151}Dy the excitation energy of a 1.3 ns isomeric state is given as 2958 keV ⁽¹¹⁾. These isomers are classified for ^{149}Gd as mainly $\nu h_{9/2}((f_{7/2})^2 \times 3^-)$ with $J^\pi = 27/2^+$ and for ^{151}Dy as $\pi(h_{11/2})^2 \nu(f_{7/2})^3$ with $J^\pi = 27/2^-$. The isomer in ^{149}Gd decays partly by an E3 transition, whereas the isomer in ^{151}Dy decays through a fairly low-energy M1 transition, followed by an E2

transition. The present experiment does not support the existence of a low-energy transition deexciting the 373 ns isomer. We therefore suggest that the 2751 keV level, as the $27/2^+$ isomeric state, deexcites directly to the $21/2^- \nu(f_{7/2})^2 h_{9/2}$ state by the 712.0 keV E3 transition, which can be identified as the analogue of the octupole transitions in neighbouring Gd nuclei. The isomeric states have about the same energy above the $((f_{7/2})^2 h_{9/2})^{9/2}$ state for ^{149}Gd and ^{153}Er . The $B(E3)$ strength of the transition in ^{153}Er is 25 W.U., which amounts to about half of the values of the corresponding transitions in the Gd nuclei. The reason for the value in Er being lower is clearly seen: The octupole excitation is mainly formed out of proton particle hole states, where a $d_{5/2}$ single particle is promoted up to the $h_{11/2}$ shell. For the Gd nuclei ($Z = 64$) all the 12 substates of the $h_{11/2}$ configuration are available, whereas for Er ($Z = 68$) only 8 substates are still empty. Thus the Pauli principle does in zero order reduce the strength with a factor $(8/12)^2 \approx 0.5$, in rough agreement with the data.

The 2751 keV isomeric state in ^{153}Er is thus interpreted as mainly due to a $h_{9/2}((f_{7/2})^2 x3^-)$ coupling on the analogy of the situation in ^{149}Gd . From our calculations, assuming a moderately oblate deformation ($\epsilon_2 \approx -0.1$) the structure of the state would be

$$|27/2^+\rangle = \nu(\alpha(f_{7/2} x3^-) + \beta i_{13/2}, K = 13/2) \nu(f_{7/2} h_{9/2}, K = 7)$$

With this interpretation of the properties of the 373 ns isomeric state, it is an yrast state. It is then interesting to note that a cascade depopulating an upper isomer (13-16) by-passes the lower isomer. As the upper isomer most probably also is an yrast state

it seems that we are here faced with a situation, where at least the main stream of the decay paths is leaving the yrast line. This situation is certainly worth a thorough study. The structure and the properties of the states above the lower isomer are at present very uncertain but at this energy the excitation of proton pairs out of the core must be taken into account.

The possibility of the 712.0 keV transition being of M1 character would necessarily involve the excitation of protons out of the core. The wave function of the isomeric state would then most probably contain a component $\pi(h_{11/2}, K = -9/2)^{-1}(h_{11/2}, K = 7/2)$. For $Z = 68$ the $h_{11/2}$ shell is occupied with 4 protons: in the oblate regime $K = 11/2$ and $9/2$ are filled. The isomer would then decay by a low-energy E2 transition to the 2751 keV level. This decay pattern would be different from what is reported by Horn *et al.*⁽¹⁶⁾, who suggest an isomeric M1 transition followed by an E2 transition (712 keV), in analogy with ^{151}Dy . Although the existence of a close-lying doublet cannot be excluded, the present experimental results are better understood without its introduction.

It is interesting to study the variation in spin-parity assignments of the traps in $N = 85$ nuclei as the proton number is increased from $Z = 64$ to 66 and 68. Obviously, two different types of configurations compete in forming the trap state; a neutron excitation, of positive parity, involving the $i_{13/2}$ shell and the $f_{7/2}$ -octupole coupling, and a proton $h_{11/2}$ particle-hole excitation, of negative parity. In Gd the latter is not possible (assuming zero deformation) and the trap therefore must involve the former type. In Dy,

however, both compete, and the proton configuration comes lowest. In Er, again, both compete but, here, the neutron excitation is most likely the winning partner. The reason for this is probably that the neutron excitation involves the $h_{9/2}(K=9/2)$ orbital, and, looking at the lower-energy part of the level scheme, the most striking difference between the $N=85$ nuclei is the decreasing trend of the $9/2$ -state as Z increases, as earlier discussed. This fact, might cause the small energy shifts needed to change the character of the yrast trap.

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REFERENCES

- 1) P. Kleinheinz, Proc. Symp. on high spin phenomena in nuclei,
Argonne 1979, ANL/PHY-79-4 (1979) p.125
P. Kleinheinz, Proc. Nobel-Symposium 50, "Nuclei at very
high spin - Sven Gösta Nilsson in Memoriam", Örenäs, Sweden,
1980, eds. G. Leander and H. Ryde, Physica Scripta 24 (1981)
236.
- 2) A Bohr and B.R. Mottelson, Physica Scripta 10A (1974) 13
- 3) G. Andersson, S.E. Larsson, G. Leander, P. Möller, S.G. Nilsson,
I. Ragnarsson, S. Åberg, R. Bengtsson, J. Dudek, B. Nerlo-
-Pomorska, K. Pomorski and Z. Szymański, Nucl. Phys. A268
(1976) 205
- 4) T. Døssing, K. Neergård, K. Matsuyanagi and Hsi-Chen Chang,
Phys. Rev. Lett. 39 (1977) 1395
- 5) J. Pedersen, B.B. Back, F.M. Bernthal, S. Bjørnholm, J. Borg-
green, O. Christensen, F. Folkmann, B. Herskind, T.L. Khoo,
M. Neiman, F. Pühlhofer and G. Sletten, Phys. Rev. Lett. 39
(1977) 990
- 6) T.L. Khoo, Proc. Int. Conf. on nuclear behaviour at high angular
momentum, Strasbourg, 1980, J. de Physique (Colloque) C10
(1980) 9

- 7) E. Hammarén, O. Häusser, H.R. Andrews, P. Taras, A. Larabee and J. Waddington, JYFL Annual Report 1980, University of Jyväskylä, Finland, p.60

- 8) J. Kownacki, Z. Sujkowski, E. Hammarén, E. Liukkonen, M. Piiparinen, Th. Lindblad, H. Ryde and V. Paar, Nucl. Phys. A337 (1980) 464

- 9) M. Piiparinen, Y. Nagai, J. Styczeń, P. Kleinheinz, Proc. Int. Conf. on nuclear behaviour at high angular momentum, Strasbourg, 1980, p.53

- 10) M. Piiparinen, R. Pengo, Y. Nagai, E. Hammarén, P. Kleinheinz, N. Roy, L. Carlén, H. Ryde, Th. Lindblad, A. Johnson, S.A. Hjorth and J. Blomqvist, Z. Phys. A300 (1981) 133

- 11) M. Piiparinen, S. Lunardi, P. Kleinheinz, H. Backe and J. Blomqvist, Z. Phys. A290 (1979) 337

- 12) L. Carlén, S. Jönsson, J. Krumlinde, J. Lyttkens, H. Ryde, S. Strömberg, G.B. Hagemann, B. Herskind and D.L. Hillis, Proc. Int. Conf. on nuclear interactions, Canberra, 1978, ed. B.A. Robson (Australian Academy of Science, Canberra, and Springer-Verlag, Berlin, 1979) p.417

- 13) S. Bjørnholm, J. Borggreen, O. Christensen, A. Del Zoppo, B. Herskind, J. Pedersen and G. Sletten, Proc. Symp. on high spin phenomena in nuclei, Argonne, 1979, ANL/PHY-79-4, p.421

- 14) D.C.J.M. Hageman, M.J.A. de Voight and J.F.W. Jansen,
Phys. Lett. 84B (1979) 301

- 15) J. Jastrzębski, J. Łukasiak, M. Moszyński, Z. Preibisz,
J. Gizon, A. Gizon, S. André and J. Genevey, Proc. EPS
Topical Conf. on large amplitude collective nuclear motions,
Keszthely, 1979, vol. 1, p.71
S. André, J. Genevey, A. Gizon, J. Gizon, J. Jastrzębski,
J. Łukasiak, M. Moszyński and Z. Preibisz, Proc. Int. Conf. on
nuclear behaviour at high angular momentum, Strasbourg, 1980, p.59

- 16) D. Horn, G.R. Young, C.J. Lister and C. Baktash, Phys. Rev.
C23 (1981) 1047

- 17) L. Carlén, CARATE - an interactive computer program for γ -
ray spectra analysis. To be published.

- 18) P.O. Tjøm, I. Espe, G.B. Hagemann, B. Herskind and D.L. Hillis,
Phys. Lett. 72B (1978) 439

- 19) O. Andersson, R. Bauer, G.B. Hagemann, M.L. Halbert, B. Hers-
kind, M. Neiman, H. Oeschler and H. Ryde, Nucl. Phys. A295
(1978) 163

- 20) P. Aguer, G. Bastin, J.P. Thibaud, D. Barneoud, J. Boutet
and C. Foin, Z. Phys. A285 (1978) 59

- 21) F. Rösel, H.M. Fries, K. Alder and H.C. Pauli, At. Data and Nucl. Data Tables 21 (1978) 291
- 22) C.G. Andersson, G. Hellström, G. Leander, I. Ragnarsson, S. Åberg, J. Krumlinde, S.G. Nilsson and Z. Szymański, Nucl. Phys. A309 (1978) 141
- 23) Table of Isotopes, seventh edition, ed. C.M. Lederer and V.S. Shirley (John Wiley & Sons, New York, 1978)

Table 1

Gamma transitions in ^{153}Er observed in the $^{144}\text{Sm}(^{12}\text{C},3n)$ reaction at 62.3 MeV bombarding energy

E_γ [keV]	Relative intensity	Ang. dist. coeff. ^{b)}		Placement $E_i \rightarrow E_f$
		A_2/A_0	A_4/A_0	
194.3	162	-0.21(06)	0.15(08)	2945.5 $\rightarrow$ 2751.2
201.7	44 ^{c)}	-0.13(17)	0.32(25)	1699.0 $\rightarrow$ 1497.5
205.1	352	-0.23(06)	0.07(09)	970.7 $\rightarrow$ 765.6
284.7	} 30	0.28(23)	-0.03(36)	4779.0 $\rightarrow$ 4494.3
284.7				4761.7 $\rightarrow$ 4477.0
292.5	37	-0.01(19)	0.17(29)	4494.3 $\rightarrow$ 4201.8
299.4	1000	-0.05(02)	0.00(03)	299.4 $\rightarrow$ 0
340.2	776	0.15(02)	-0.05(02)	2039.2 $\rightarrow$ 1699.0
349.2	43	-0.25(13)	0.77(19)	5182.5 $\rightarrow$ 4833.3
356.3	52	-0.33(12)	-0.17(17)	4833.3 $\rightarrow$ 4477.0
363.1	127 ^{d)}	0.07(04)	0.11(06)	3312.3 $\rightarrow$ 2949.2
418.4	58	0.36(08)	-0.12(12)	4477.0 $\rightarrow$ 4058.6
530.2	134	0.24(04)	-0.08(06)	2908.5 $\rightarrow$ 2378.3
588.1	833	0.15(02)	-0.09(02)	1699.0 $\rightarrow$ 1110.9
653.2	506 ^{e)}	0.19(02)	-0.10(03)	2378.3 $\rightarrow$ 1725.1
692.8	108 ^{f)}	0.25(09)	-0.05(14)	4201.8 $\rightarrow$ 3509.0
696.6	59 ^{f)}	0.32(10)	-0.11(16)	2194.1 $\rightarrow$ 1497.5
712.0	502	0.00(02)	0.00(03)	2751.2 $\rightarrow$ 2039.2
731.9	145	0.14(05)	-0.03(08)	1497.5 $\rightarrow$ 765.6
746.3	103	0.27(05)	-0.02(07)	4058.6 $\rightarrow$ 3312.3
754.4	256	0.28(03)	-0.13(04)	1725.1 $\rightarrow$ 970.7
757.8	120	0.25(05)	-0.13(07)	3509.0 $\rightarrow$ 2751.2
765.6	585	0.27(02)	-0.15(03)	765.6 $\rightarrow$ 0
811.5	916	0.18(02)	-0.08(02)	1110.9 $\rightarrow$ 299.4
910.0	147	0.28(04)	-0.08(07)	2949.2 $\rightarrow$ 2039.2

a) Energy uncertainties are estimated from 0.1 keV for strong transitions up to 0.5 keV for weak transitions

b) Only fitting errors are included.

c) Not corrected for contamination from ^{154}Er .

d) Not corrected for contamination from ^{153}Ho .

e) Not corrected for contamination from ^{150}Dy .

f) Problems with background from Ge ($n,n'\gamma$).

Table 2

Coincidences in ^{153}Er from the reaction $^{144}\text{Sm}(^{12}\text{C}, 3n)$ at 63.0 MeV bombarding energy

Gate E_γ [keV]	Coincident γ -rays [keV]
194.3	299.4, 340.2, 429 ⁵⁾ , 588.1, 659.3 ¹⁾ , 712.0, 811.5
201.7	340.2, 456.0 ²⁾ , 507.2 ²⁾ , 560.6 ²⁾ , 601.3 ²⁾ , 625 ²⁾ , 669.1 ²⁾ , 731.9, 765.6
205.1	351.4 ¹⁾ , 530.2, 653.2, 754.4, 765.6
284.7	292.5, 299.4, 340.2, 363.1, 418.4, 588.1, 746.3, 811.5, 910.0
292.5	284.7, 299.4, 318.6 ¹⁾ , 340.2, 692.8, 757.8
299.4	194.3, 284.7, 340.2, 349.2, 356.3, 363.1, 418.4, 588.1, 712.0, 746.3, 757.8, 787.1 ⁵⁾ , 811.5, 910.0
340.2	194.3, 201.7, 284.7, 299.4, 349.2, 356.3, 363.1, 418.4, 588.1, 712.0, 731.9, 746.3, 757.8, 765.6, 811.5, 910.0
349.2	201.7, 299.4, 340.2, 356.3, 363.1, 418.4, 588.1, 746.3, 811.5, 910.0
356.3	299.4, 340.2, 349.2, 363.1, 418.4, 588.1, 746.3, 811.5, 910.0
363.1	284.7, 299.4, 340.2, 349.2, 356.3, 418.4, 532.5 ³⁾ , 557.0 ³⁾ , 588.1, 631.1 ³⁾ , 746.3, 811.5, 910.0, 912.9 ³⁾
418.4	284.7, 299.4, 340.2, 349.2, 356.3, 363.1, 588.1, 746.3, 811.5, 910.0
530.2	205.1, 653.2, 754.4, 765.6
588.1	194.3, 284.7, 299.4, 340.2, 349.2, 356.3, 363.1, 418.4, 712.0, 746.3, 757.8, 787.1 ⁵⁾ , 811.5, 910.0
653.2	205.1, 393.9 ⁴⁾ , 403.6 ²⁾ , 411.1 ⁴⁾ , 530.2, 542.0 ²⁾ , 551.0 ⁴⁾ , 560.6 ²⁾ , 601.3 ²⁾ , 619.4 ²⁾ , 625.7 ²⁾ , 637.7 ²⁾ , 688.4 ²⁾ , 754.4, 765.6, 803.9 ⁴⁾
692.8	292.5, 335.0 ¹⁾ , 757.8
696.6	731.9, 765.6
712.0	194.3, 299.4, 340.2, 588.1, 757.8, 765.6, 811.5
731.9	201.7, 340.2, 696.6, 765.6
746.3	284.7, 299.4, 340.2, 349.2, 356.3, 363.1, 418.4, 588.1, 811.5, 910.0
754.4	205.1, 530.2, 653.2, 765.6
757.8	284.7, 292.5, 299.4, 340.2, 692.8
765.6	194.3, 201.7, 205.1, 340.2, 530.2, 653.2, 696.6, 754.4, 776.0 ¹⁾ , 910.0
811.5	194.3, 284.7, 299.4, 340.2, 349.2, 356.3, 363.1, 418.4, 588.1, 712.0, 746.3, 757.8, 910.0
910.0	284.7, 299.4, 340.2, 349.2, 363.1, 418.4, 588.1, 746.3, 811.5

1) Unassigned transitions.

2) Transitions assigned to ^{154}Er .3) Transitions assigned to ^{153}Ho .4) Transitions assigned to ^{150}Dy .5) Transitions assigned to ^{153}Er but not placed in the level scheme.

FIGURE CAPTIONS

- Fig.1 The Ge(Li) γ -ray spectra obtained with a gate placed on the low-energy part (upper spectrum) and on the high-energy part (lower spectrum) of the sum-spectrum recorded in a NaI(Tl) detector subtending a solid angle of 70% of 4π . The γ -ray energies given in table 1 are marked with arrows.
- Fig.2 Excitation functions for some γ -rays assigned to transitions in ^{153}Er and normalized to the intensity of the 299.4 keV γ -line.
- Fig.3 The average multiplicities (open circles) and standard deviations (filled circles) for some transitions in ^{153}Er as a function of the bombarding energy.
- Fig.4 Time distribution of the intensities of the γ -rays de-exciting the 2751.2 keV isomeric state.
- Fig.5 Experimental conversion coefficients for transitions in Er ($Z=68$). Full drawn curves are theoretical values from ref. (21).
- Fig.6 Spectra of coincident γ -rays observed with gates at 299, 340, 712 and 910 keV.
- Fig.7 Spectra of coincident γ -rays observed with gates at 765 and 754 keV. The appearance of the 194.3 and 776.0 keV transitions in the 765.6 keV gate have not been explained.
- Fig.8 Level scheme of ^{153}Er . The figure shows the decay pattern at 64.5 MeV. Spin and parity assignments are based on the present experimental results and comparisons with adjacent $N=85$, even- Z nuclei.
- Fig.9 Energy levels of even- Z isotones with $N=85$ for different configurations.

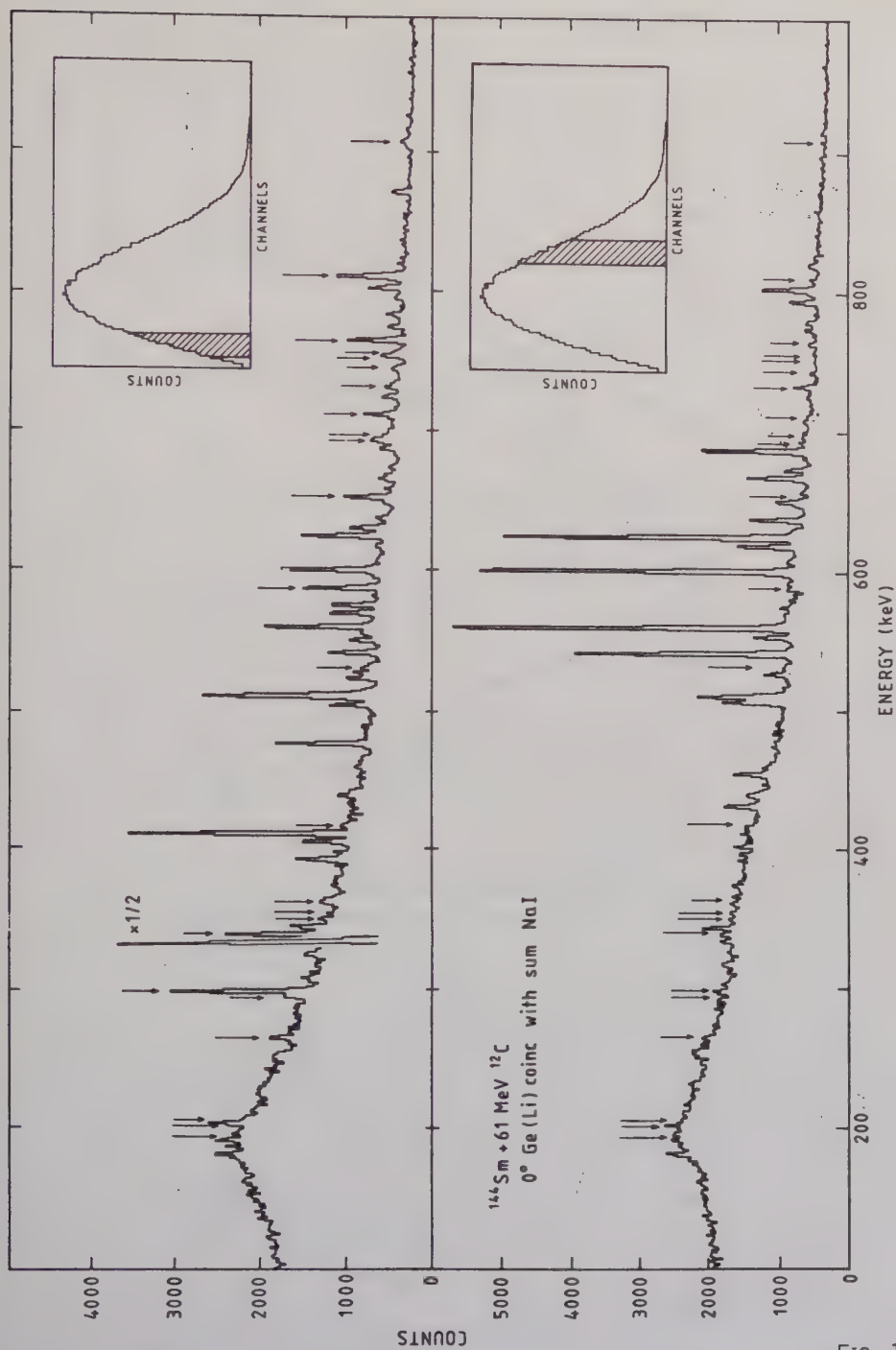


FIG. 1

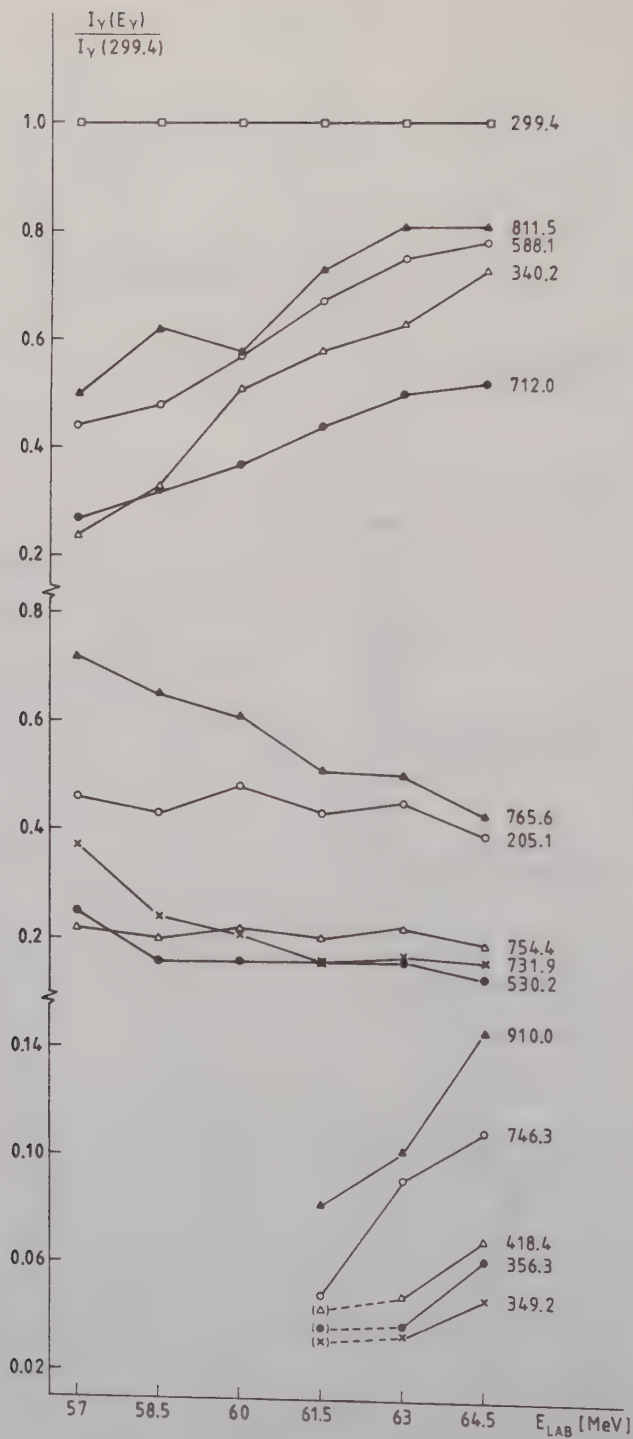


FIG. 2

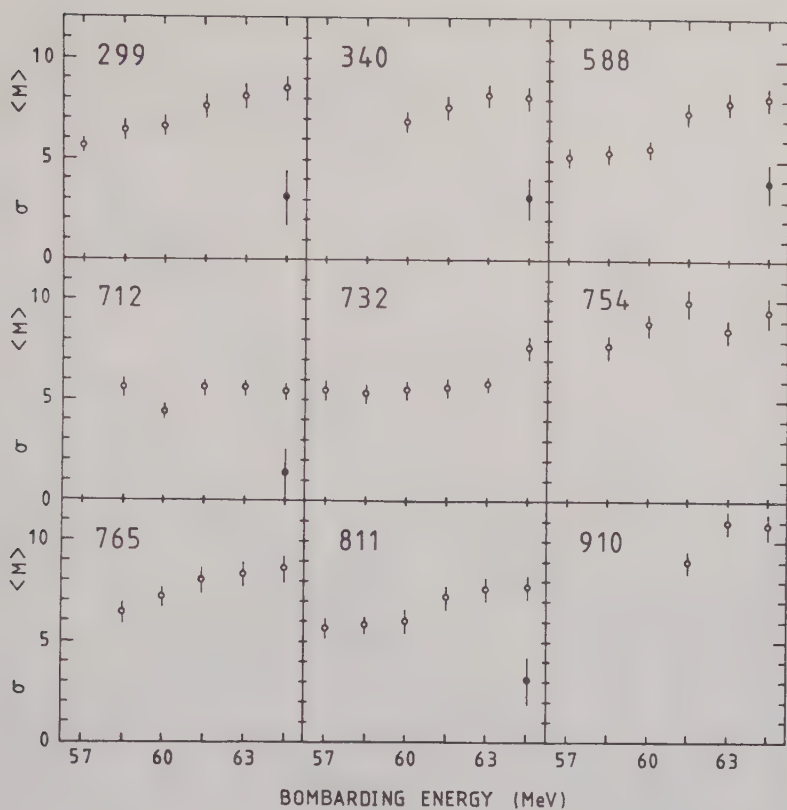


FIG. 3

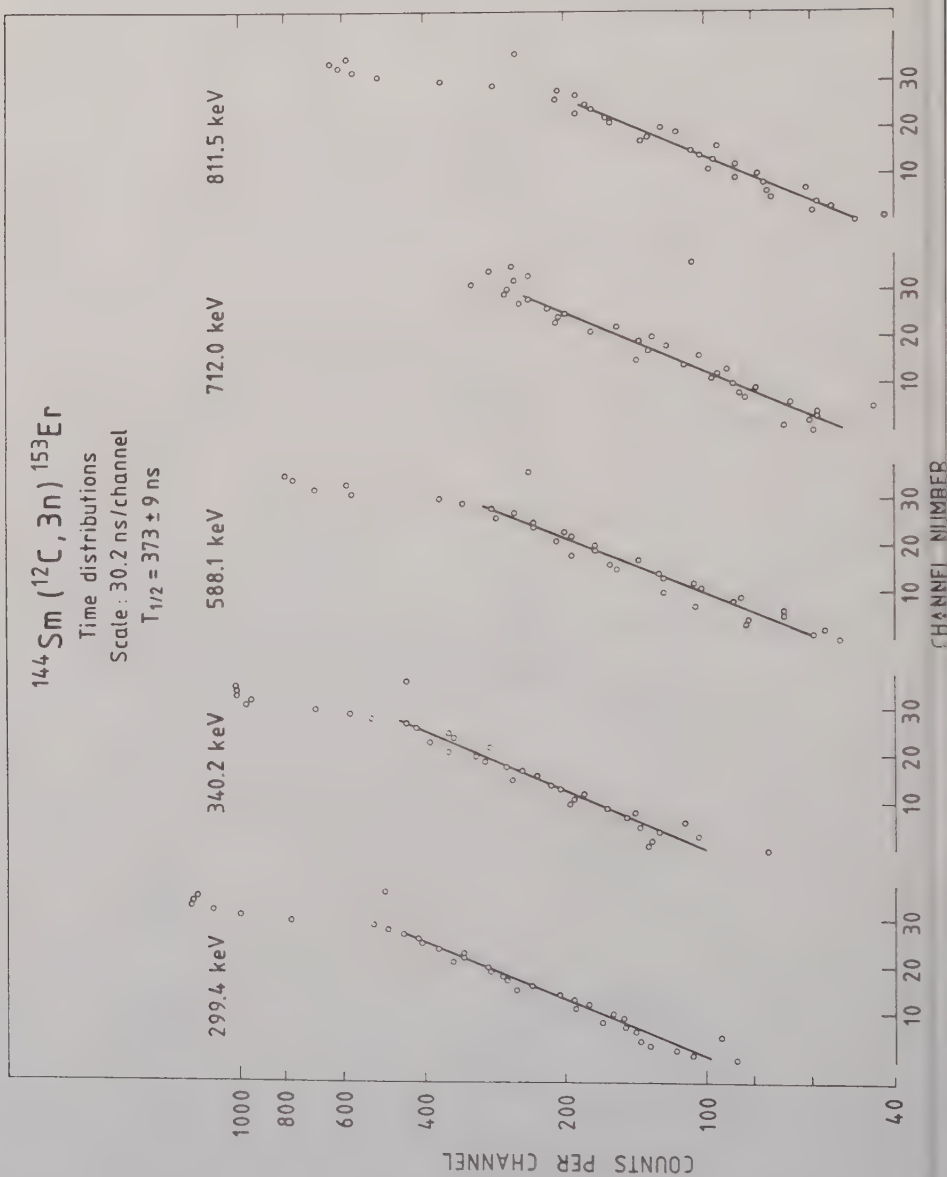


FIG. 4

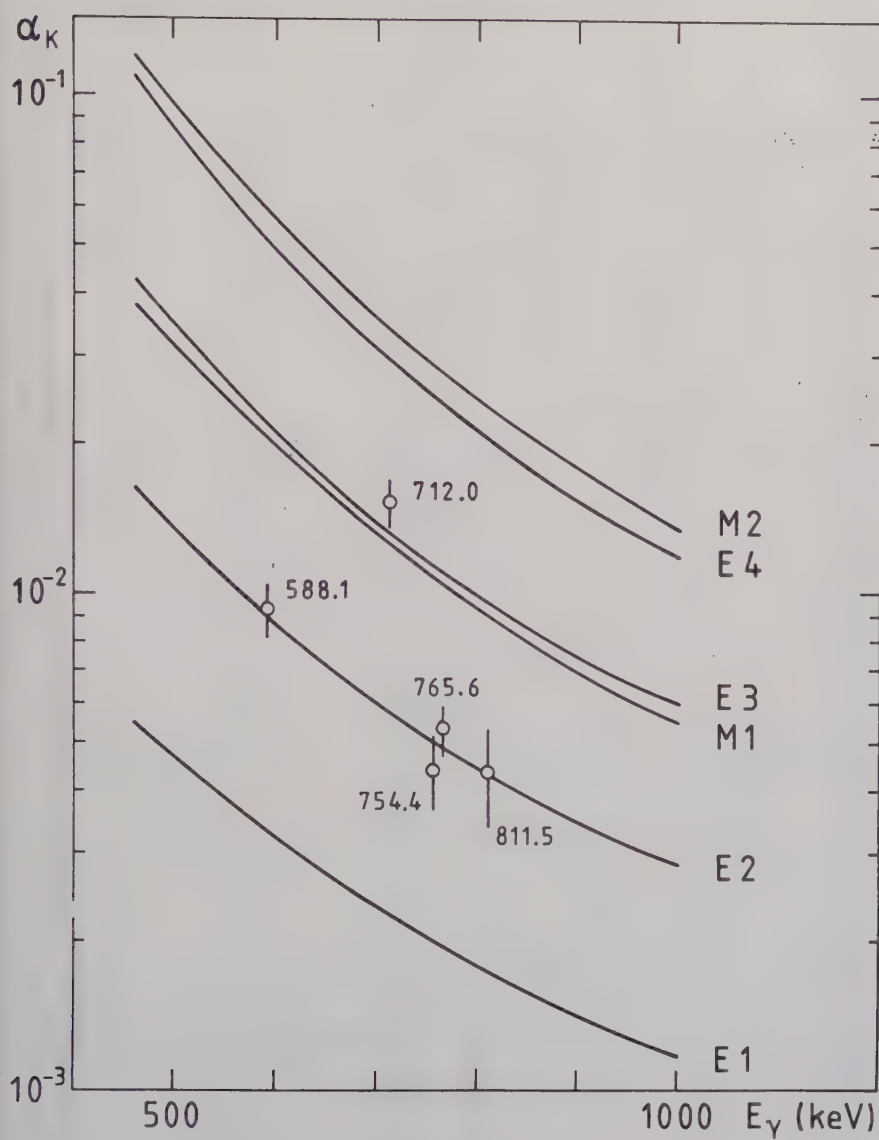


FIG. 5

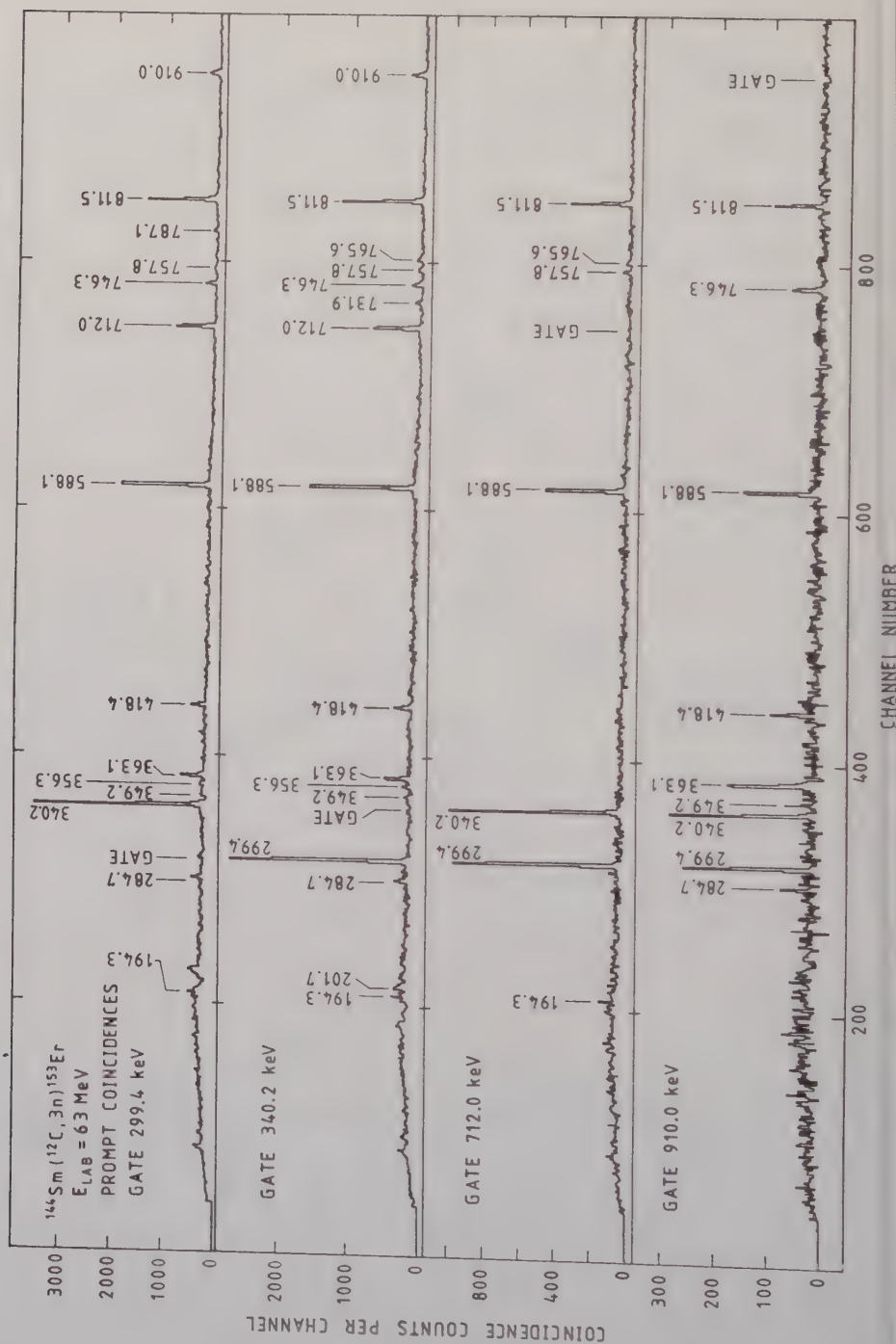


FIG.

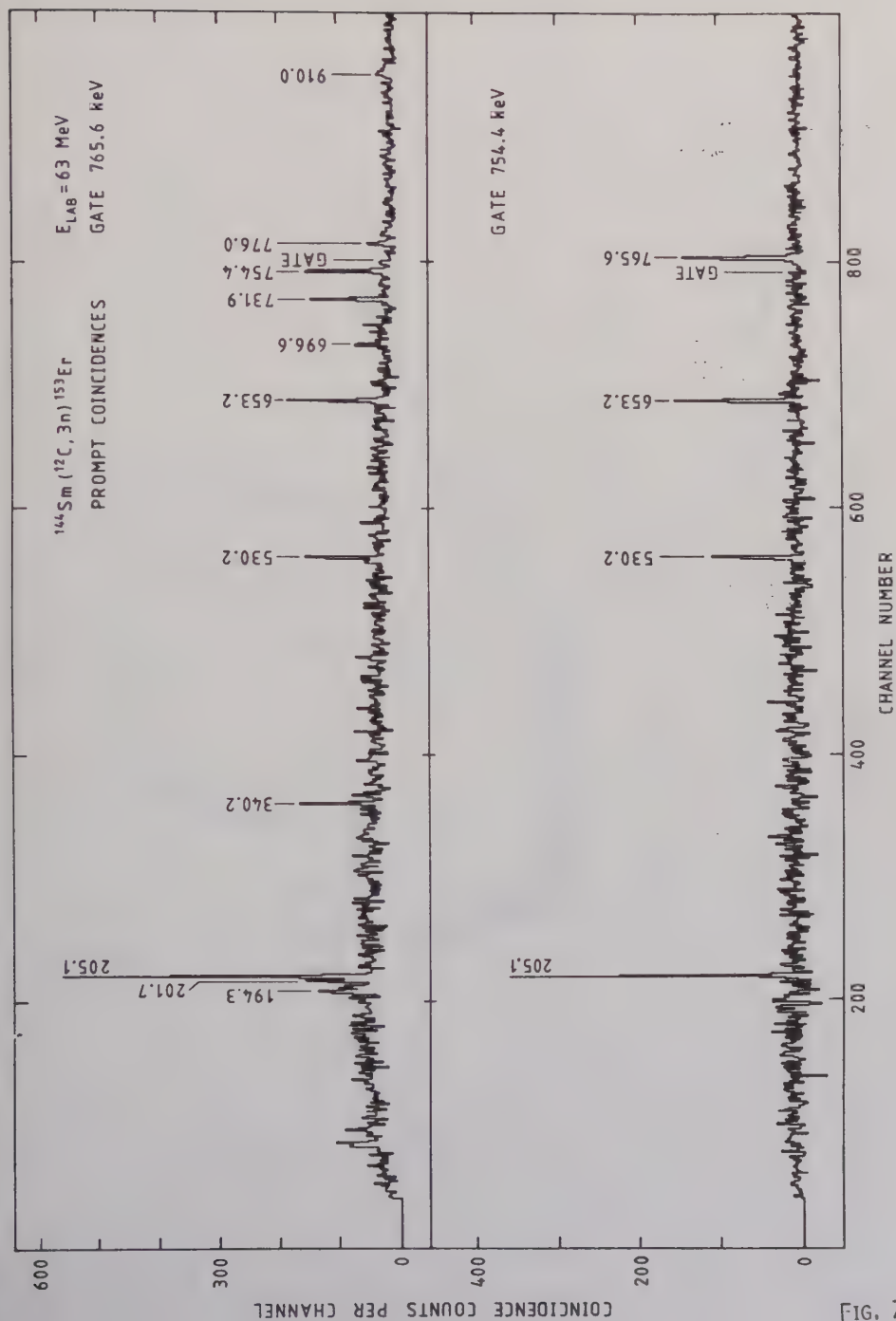


FIG. 7

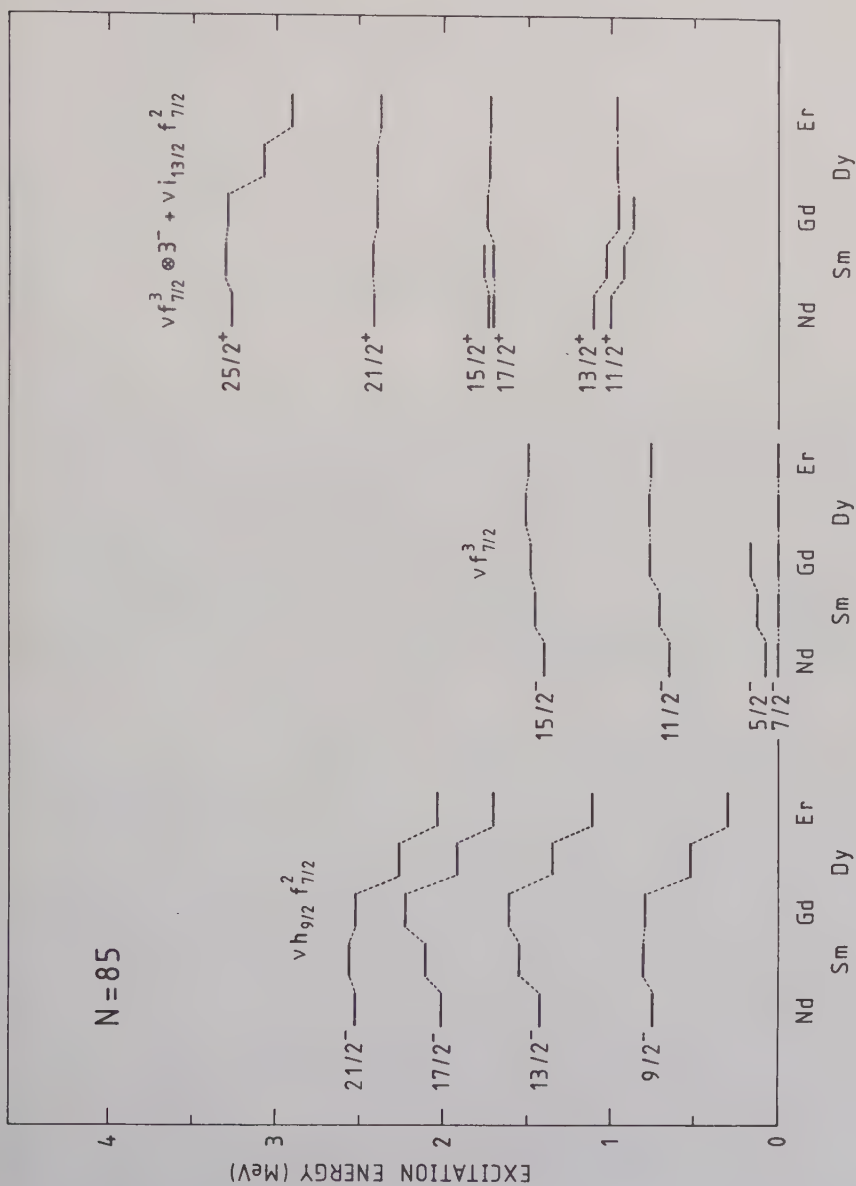


FIG. 9

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HIGH SPIN STATES AND YRAST ISOMERISM IN ^{153}Er .

Referat (sammmandrag)

Energy levels in ^{153}Er have been populated in the reaction $^{144}\text{Sm}(^{12}\text{C},3n)^{153}\text{Er}$. Isotopically enriched targets were bombarded with 53-65 MeV ^{12}C ions and the emitted γ -ray and conversion electron spectra were investigated. From studies of excitation functions, γ - γ coincidences, γ -ray multiplicities, delayed γ -radiation and angular distributions, the level scheme of ^{153}Er has been constructed. The properties of the energy levels are discussed and compared with the results of calculations with a deformed shell model. The remarkable similarities and some important discrepancies of the level structure, when compared with adjacent $N=85$ nuclides, are emphasized.

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High-Spin Band Structure in ^{166}Yb

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Abstract

High-spin states in ^{166}Yb have been studied via the $^{154}\text{Sm}(^{16}\text{O}, 4n)^{166}\text{Yb}$ reaction with 80 MeV ^{16}O ions from the NBI tandem accelerator. γ - γ coincidence data were accumulated with an array of four Ge(Li) and four NaI(Tl) detectors to favour high multiplicity events. Totally about 3×10^5 events were accumulated in the coincidence experiment. Measurements of the angular distribution of the γ -radiation and the conversion coefficients were furthermore performed. Four weakly populated side bands are observed besides the yrast cascade which is followed up to its 24^+ member. The ground state band has thus been identified to its 18^+ state, while the crossing Stockholm band becomes the yrast band from its 16^+ member. The S-band is established from its 12^+ state. The observed level energies and transition rates are well reproduced in calculations within the particle rotor model.

1. Introduction

In the mass region $A = 150$ –170 the S-(Super or Stockholm) band [1] built upon aligned $(\nu_{13/2})^2$ orbits, usually crosses the ground state band (g.s.b.) around spin 14 and may cause back-bending, depending upon the interaction between the g.s. and S-band. The interpretation of the band structure and band crossings in rotational nuclei along the lines of Bohr and Mottelson [1] provides us with a means to compare experimental results with a microscopic theory and to extract quantities like the crossing frequency and the aligned angular momentum from the experimental data. The nucleus ^{166}Yb is of special interest, because *a priori* it would seem to be one of the best rotors which can be significantly populated at very high spins by (HI, xn) reactions. The identification of discrete lines in this work extends the information about the non-yrast bands from lighter and less rotational-like nuclei, and furthermore complements the gamma correlation work described elsewhere in these proceedings [2].

2. Experimental technique and results

States in ^{166}Yb were populated following the $^{154}\text{Sm}(^{16}\text{O}, 4n)^{166}\text{Yb}$ reaction at a beam energy of 80 MeV, the beams being provided by the NBI tandem accelerator. The experiments con-

sisted of γ -ray angular distribution, γ - γ coincidence and conversion electron coefficient measurements. The reaction yields at this bombarding energy, with an isotopically enriched, metallic target of ^{154}Sm sputtered to a thickness of 1.5 mg cm^{-2} onto a lead backing, were about 77% ^{166}Yb , 15% ^{165}Yb and 7% ^{167}Yb .

2.1. Singles γ -ray measurements

With the target at an angle of 45° relative to the beam direction two sets of singles γ -ray spectra were obtained at 5 different angles, one with a Ge(Li) detector at angles ranging between 58° and 148° and the other with a Ge(Li) detector in a Compton-suppression set-up at angles between 0° and 90° . One stationary Ge(Li) detector placed below the target served as the monitor. In spite of the low counting rate, the data for the weak transitions obtained with the anti-Compton set-up proved to be superior to those with the other detector due to the reduced background. Efficiency calibrations at various angles were performed with a radioactive ^{152}Eu source placed at the target position. A typical spectrum obtained with the anti-Compton set-up at 90° is shown in Fig. 1. Two sets of angular distribution coefficients were obtained, one for each detector, by fitting the peak intensities to the expression $W(\theta) = A_0 + A_2 P_2(\cos \theta) + A_4 P_4(\cos \theta)$, after normalizing them to the monitor yields and correcting for the dead times of the ADCs and the variations of the relative efficiency at different angles. The results from the two detector set-ups are consistent. The results of the angular distribution measurements are summarised in Table I. The energy calibration was done by recording a singles γ -ray spectrum at 90° along with the spectrum from a ^{152}Eu source placed near the target.

2.2. γ - γ coincidence measurements

γ - γ coincidence measurements were performed with an array of four Ge(Li) detectors and four NaI(Tl) detectors. The gains of the amplifier of the Ge(Li) detectors were matched to be equal. Only those coincidence events were accumulated on magnetic tape for off-line analysis, for which two Ge(Li) counters in addition to at least one of the remaining Ge(Li) detectors or one of the NaI(Tl) detectors were triggered. In all, about 300 million pairs of events were accumulated. The tapes were sorted for all the possible combinations of pairs of detectors and the resulting spectra, after background subtrac-

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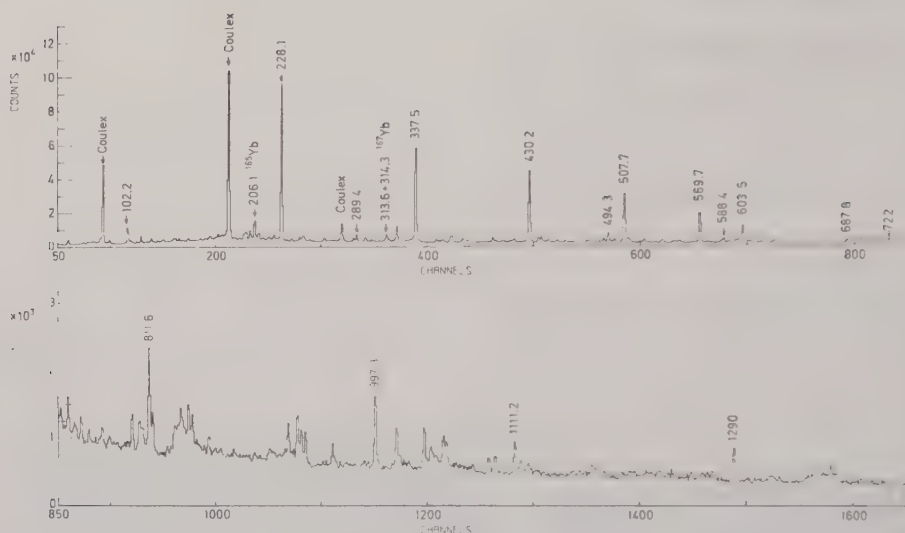


Fig. 1. Singles γ -ray spectrum at 90° to the beam direction, using an anti-Compton set-up, taken during bombardment of a ^{154}Sm target with 80 MeV ^{16}O .

Table I. The energies, intensities and angular distribution coefficients for the transitions assigned to ^{166}Yb following the $^{154}\text{Sm}(^{16}\text{O}, 4n)^{166}\text{Yb}$ reaction at 80 MeV

E_γ^a (keV)	Intensity ^b	Ang. dist. coeff. ^c		$I_1^{pd} \rightarrow I_2^{pd}$
		A_2/A_0	A_4/A_0	
102.2		0.27(03)	-0.06(03)	$2^+ \rightarrow 0^+$
114				$8^- \rightarrow 7^-$
152				$10^- \rightarrow 9^-$
206 ^e	16	0.21(07)	-0.05(08)	$8^- \rightarrow 6^-$
228.1	987	0.30(03)	-0.09(03)	$4^+ \rightarrow 2^+$
248 ^e	8			$6^- \rightarrow (4^-)$
274 ^e	Weak			$(7^-) \rightarrow (7^-)$
276 ^e	Weak			$(7^-) \rightarrow (6^-)$
289 ^e				$(4^-) \rightarrow 5^+$
289.4	55	0.30(02)	-0.10(02)	$10^- \rightarrow 8^-$
301.4	14	0.42(05)	0.02(05)	$(8^-) \rightarrow (6^-)$
337.5	1000	0.32(03)	-0.11(03)	$6^+ \rightarrow 4^+$
341	Weak			$(10^-) \rightarrow 9^+$
354.4	28	0.28(03)	-0.03(04)	$(10^-) \rightarrow (8^-)$
356 ^e	16			$12^+ \rightarrow 12^+$
366 ^e	5			$14^+ \rightarrow 12^+$
367.6 ^e	65	0.29(02)	-0.15(02)	$12^- \rightarrow 10^-$
368 ^e				$(7^-) \rightarrow 6^-$
375.8	37	0.27(02)	-0.12(03)	$16^+ \rightarrow 14^+$
400.4	51	0.34(03)	-0.10(03)	$(12^-) \rightarrow (10^-)$
403 ^e	17			$17^- \rightarrow 16^-$
430.2	856	0.31(03)	-0.13(03)	$8^+ \rightarrow 6^+$
432 ^e	Weak			$(8^-) \rightarrow 7^+$
437.6	63	0.27(03)	0.08(03)	$14^- \rightarrow 12^-$
445.8 ^e				$13^- \rightarrow 11^-$
446 ^e	33	0.14(09)	-0.02(07)	$9^+ \rightarrow 7^+$
459.4	27	0.36(05)	-0.19(05)	$(14^-) \rightarrow (12^-)$
490.8	43	0.32(06)	-0.07(09)	$15^- \rightarrow 13^-$
494.3	128	0.35(010)	-0.09(01)	$16^+ \rightarrow 14^+$
496.7	22	0.38(04)	-0.18(05)	$(11^-) \rightarrow 9^+$

Table I. (continued)

E_γ^a (keV)	Intensity ^b	Ang. dist. coeff. ^c		$I_1^{pd} \rightarrow I_2^{pd}$
		A_2/A_0	A_4/A_0	
499.5	45	0.33(03)	-0.13(03)	$16^- \rightarrow 14^-$
507.7	645	0.32(08)	-0.09(01)	$10^+ \rightarrow 8^+$
508 ^e				$(6^-) \rightarrow 5^+$
509 ^e	160	0.23(03)	-0.11(03)	$18^+ \rightarrow 16^+$
527.5	14	0.26(07)	-0.01(11)	$(16^+) \rightarrow (14^+)$
538 ^e	19	-0.26(24)	-0.16(25)	$6^- \rightarrow 5^+$
538.2 ^e	35	0.47(13)	0.04(14)	$17^- \rightarrow 15^-$
550 ^e	15	0.22(04)	0.03(07)	$13^- \rightarrow 11^-$
552.8	32	0.20(05)	-0.03(08)	$18^- \rightarrow 16^-$
569.7	480	0.33(03)	-0.11(03)	$12^- \rightarrow 10^-$
575.1	17	-0.30(18)	0.15(17)	$15^- \rightarrow 14^-$
586.2 ^e	30	0.22(07)	0.34(09)	$19^- \rightarrow 17^-$
588.4	69	0.36(05)	-0.02(08)	$20^+ \rightarrow 18^+$
592 ^e	14			$16^+ \rightarrow 14^+$
592 ^e	10	0.27(17)	-0.07(22)	$(18^-) \rightarrow (16^-)$
600.1	25	0.25(12)	0.05(13)	$20^- \rightarrow 18^-$
603.5	250	0.31(02)	-0.13(02)	$14^+ \rightarrow 12^+$
629 ^e				$(6^-) \rightarrow 5^+$
630 ^e	24	0.29(03)	-0.05(07)	$21^- \rightarrow 19^-$
649 ^e	10			$22^- \rightarrow 20^-$
649 ^e	Weak			$(20^-) \rightarrow (18^-)$
660 ^e	7			$5^+ \rightarrow 6^+$
667	25	Doppler broadened		$22^+ \rightarrow 20^+$
674 ^e	13	0.13(09)	-0.33(09)	$23^- \rightarrow 21^-$
687.8	45	-0.21(02)	0.10(03)	$13^- \rightarrow 12^-$
701				$18^- \rightarrow 16^-$
709 ^e	4			$3^+ \rightarrow 4^+$
710.3	39	0.34(03)	-0.02(05)	$16^+ \rightarrow 14^+$
722.0	69	0.35(01)	-0.05(02)	$14^+ \rightarrow 12^+$
739		Doppler broadened		$24^+ \rightarrow 22^+$

Table I. (continued)

E_{γ} (keV)	Intensity ^b	Ang. dist. coeff. ^c		I_{α}^{e} ^d → I_{β}^{e} ^d
		A_2/A_0	A_4/A_0	
811.6	39	−0.15(07)	0.01(06)	11 [−] → 10 ⁺
830 ^f	22			2 ⁺ → 2 ⁺
860	10			(7 [−]) → 8 ⁺
925.6	15	0.27(05)	−0.16(07)	12 ⁺ → 10 ⁺
932 ^f	21			2 ⁺ → 0 ⁺
936 ^f	16			3 ⁺ → 2 ⁺
997.3	38	−0.19(03)	0.15(07)	5 ⁺ → 4 ⁺
1037	22	−0.31(06)	0.05(07)	7 ⁺ → 6 ⁺
1053	16	−0.31(07)	0.03(08)	9 ⁺ → 8 ⁺
1111.2	19	−0.22(04)	0.04(05)	9 [−] → 8 ⁺
1122	8			(5 [−]) → 6 ⁺
1290	25	−0.19(04)	0.06(04)	(7 [−]) → 6 ⁺
1460 ^e				(5 [−]) → 4 ⁺

^a Energy uncertainties are 0.2 keV for strong transitions (rel. int. > 50), rising to 0.5 keV for weaker transitions.
^b Intensities are given relative to the 6⁺ → 4⁺ g.s.b. transition.
^c Only fitting errors are given.
^d Assignments in brackets are tentative.
^e Weak or doublet. Intensities wherever given for individual transitions, are based on the coincidence data, uncorrected for the angular correlation effects.
^f Lines known from the decay of ¹⁶⁴Lu. Assignments are based on the observed branching ratios.

tion, were added together. Examples of coincidence spectra are shown in Fig. 2. In a similar coincidence run for studying the ¹⁶⁷Yb nucleus with an 80 MeV ¹⁷O beam, the yield of ¹⁶⁶Yb was about 50% with no observable yield found for ¹⁶⁵Yb. As many transitions in ¹⁶⁵Yb have the same or nearly the same energy as those in ¹⁶⁶Yb, the data from the latter experiment helped to remove ambiguities concerning many weak transitions and to confirm the level scheme of ¹⁶⁶Yb.

2.3. Conversion coefficient measurements

In order to ascertain the multipolarities of the transitions, the conversion electron spectrum was obtained at 55° with a solenoid transporter and a cooled Si(Li) detector. The electron intensities were recorded in the range from about 600 keV to about 1200 keV as this region contained most of the interband transitions. A γ-ray-spectrum was also recorded simultaneously at −55°. The conversion coefficients were normalized to the α_K(E2) values of the 603, 710 and 722 keV transitions. The results of the conversion coefficient measurements have led to the assignment of negative parity of two side bands.

3. Construction of the level scheme

The yrast sequence of levels in ¹⁶⁶Yb was earlier known up to spin 20⁺. Many low-lying levels up to an excitation energy of 2.43 MeV are known from the radioactive decay studies [3] of ¹⁶⁶Lu. The level scheme of ¹⁶⁶Yb, as deduced from the present work, is presented in Fig. 3. Previously known levels, not seen in this work, are not included in the figure. The spin and parity assignments are based on the angular distribution and conversion coefficient measurements with frequent reference to previous measurements. All the transitions within a band are found to be of stretched E2 character. The ordering of the transitions within a band is based on their coincidence relationships and their relative intensities.

3.1. The ground state and S-bands

The yrast sequence of levels has been extended up to a spin of 24⁺ and the g.s.b. to a spin of 18⁺. Although the 667 and 739 keV lines, depopulating the 22⁺ and the 24⁺ levels, respectively, show considerable Doppler broadening, their angular anisotropies are well enough determined and have the same magnitude as expected for stretched E2 transitions high up in a

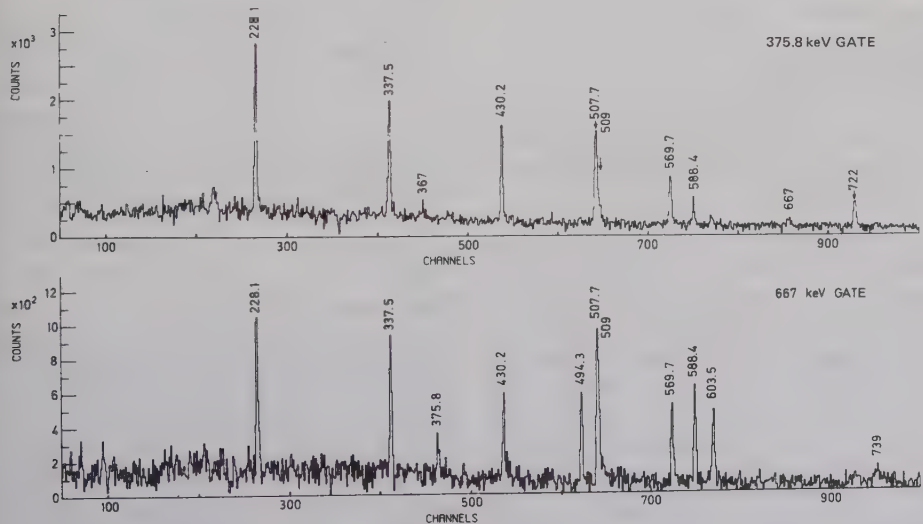


Fig. 2. Ge(Li) γ-γ coincidence spectra (background - subtracted) observed following the ¹⁵⁴Sm(¹⁶O, 4n)¹⁶⁶Yb reaction at 80 MeV.

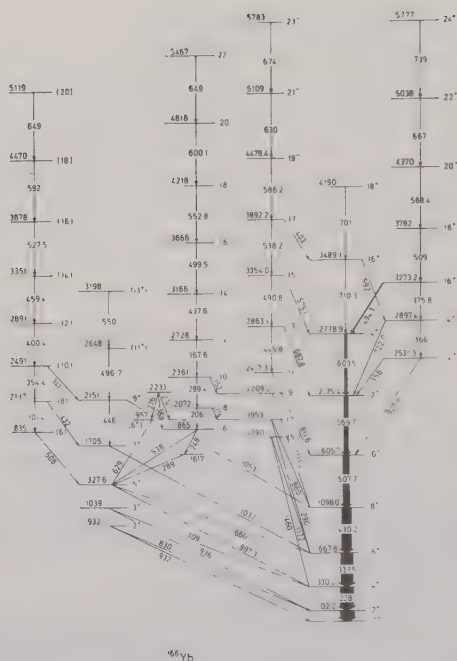


Fig. 3. Level scheme of ^{166}Yb showing states populated by the $^{156}\text{Sm}(^{16}\text{O}, 4n)^{166}\text{Yb}$ reaction.

cascade, and thereby justify their assignments. The 356 keV transition from the $12''$ to the 12^+ state could only be inferred from the coincidence data. Its intensity, the angular distribution coefficients and hence the M1/E2 mixing ratio could not be determined due to the presence of a contaminant line from the radioactive decay of the reaction products. The intensity of the 592 keV 16^+ to 14^+ state transition could only be inferred from the coincidence data due to the presence of another transition having nearly the same energy.

3.2. The odd-spin negative parity band

One band with odd-spin and negative parity has been identified. The 11^- member of this band and the higher lying members are joined by a cascade of stretched quadrupole transitions and connected to the g.s.b. by four interband transitions. The measured K -conversion coefficient of the 688 keV transition confirms the negative parity assignment of this band. The intensity ratios of the intraband transitions to the interband transitions to the g.s.b. decrease going down the band. The intraband transitions among the $5^-, 7^-, 9^-$ and the 11^- states at 1790, 1959, 2209 and 2417 keV are too weak to be detected in the coincidence work. The 5^- and 7^- states are known from the work of de Boer et al. [3]. The stretched E1 character of the transition from the 9^- state to the 8^+ member of the g.s.b. is established from angular distribution and conversion coefficient measurements.

3.3. The even-spin negative parity band

The level at 1865 keV, which lies at the bottom of the even-spin negative parity band, has been observed in the radioactive decay of ^{166}Lu [3] and assigned a spin and parity of 6^- . The regularity and the stretched E2 character of the cascade transitions populating this level justify the classification of this cascade as a band. Furthermore, the state 10^- at 2361 keV decays by an intense, mixed transition to the level at 2209 keV, which is assigned as having spin and parity 9^- in this study. This mixed transition is assumed to be of the M1/E2 type. Multipole admixture of higher order than quadrupole would require the level at 2361 keV to be an isomer with a lifetime of the order of microseconds.

3.4. The γ -vibrational band

Several members of the γ -vibrational band have been observed earlier in the radioactive decay of ^{166}Lu [3]. The 5^+ member of this band is populated rather strongly in the present study and angular distribution and the conversion electron data confirm the 5^+ assignment. The 2^+ and 3^+ levels are populated very weakly and we infer their presence in this study from the observed branching ratios of the decays of these levels. The 7^+ level at 1705 keV has been found to decay by a stretched M1 transition to the 6^+ state of the g.s.b. It is to be noted that this level is not the same as the 7^+ level found earlier [3]. The assignment of the higher lying members of this band is only tentative and is based upon the observed decay properties of these levels, the systematic variation of the level differences and the similarity to the $N = 96$ isotope ^{164}Er .

3.5. An unassigned rotational band and further levels

A band of levels of unknown spins and parity and built on the 1835 keV state is observed in the present study. This band is connected by means of three weak interband transitions to the proposed γ -vibrational band, and the energies of these transitions are too close to strong g.s.b. transitions to make a determination of their multipole character possible in the present experiment. The tentatively suggested spins and negative parity are based on the observation of a similar band in ^{164}Er starting in that case with spin (8) at an excitation energy of 2091 keV.

The levels at 1617, 1957 and 2233 keV (cf. Fig. 3) are known from the work of de Boer et al. [3]. Our identification of these levels is based solely on the observation of some transitions originating from these levels in our coincidence spectra. Only these transitions are shown in Fig. 3 and other decay modes of these levels, not established in the present study, are excluded from the figure.

4. Theoretical considerations

A crossing of two bands is sometimes referred to as virtual or real, depending on whether or not an interaction between the two bands is likely to deflect a gamma cascade from one band to another. The real crossing known in the deformed rare-earth nuclei all occur between bands which do not interact because of different signature or parity. The crossings between the g.s. and S-bands, on the other hand, are generally virtual and an yrast cascade tends to stay yrast. However, it is illustrated by the case of ^{166}Yb that even when the interaction between the bands is not forbidden, there may be situations when the nucleus prefers to follow a band of given structure rather than

the trajectory of lowest energy, In Section 4.1 the general conditions for such behaviour are formulated in terms of the band parameters. In Section 4.2 it is pointed out that the different cascade patterns in the two $N = 96$ isotones ^{164}Er and ^{166}Yb arise naturally in particle-rotor calculations based on the notion of $(\nu i_{3/2})^2$ bands crossing the ground band. Section 4.3 contains a phenomenological analysis in terms of cranking model quantities for the positive and negative parity bands shown in Fig. 3.

4.1. Two-band analysis

A schematic model can be used to derive the conditions when a crossing between two weakly interacting bands is mainly virtual or mainly real. The energies of the two unperturbed bands as functions of the spin I are written

$$E = A_i(I - J_i)^2 + E_i^0, \quad i = 1, 2$$

They cross at a spin I_c . The difference $J_2 - J_1$ between the aligned spins is denoted j . Perturbed bands are obtained by diagonalizing a two by two matrix with an off-diagonal matrix element V . It is then straightforward to find the perturbed energies and the relative transition rates. The branching ratio of the transition rates from the lowest state of spin I to the upper and lower states of spin $(I - 2)$ are, in two special cases

$$\frac{T(I_c \rightarrow I_c - 2)}{T(I_c \rightarrow (I_c - 2)')} = \left[\frac{1}{1 - (j/I_c)} \right]^5 + O(V)$$

and

$$\frac{T(I_c + 1 \rightarrow I_c - 1)}{T(I_c + 1 \rightarrow (I_c - 1)')} = \frac{V \left[1 - \frac{1}{2}(j/I_c) \right]^5}{A_i \left[1 - (j/I_c) \right]} + O(V^2)$$

respectively. In the first case the bands cross at one of the discrete spins where states exist, and it is seen that the yrast cascade tends to remain yrast. In the second case, where the bands cross in between the discrete states, the yrast cascade tends to leave the yrast line if V is sufficiently small. For given A and j this situation is clearly favoured by a large spin I_c .

A two-band analysis along the lines of [4] for the energy levels of ^{164}Er and ^{166}Yb is described in Section 4.3 below. It gives $I_c \sim 16$ in the former nucleus and $I_c \sim 15$ in the latter which thus accounts for the observed difference in the gamma cascade of the two nuclei. Other parameters obtained from the two-band analysis are the interaction V between the two unperturbed bands, and the inertia parameters. The branching ratios of the decays of the g.s. and the S-band suggest an interaction V of the order of 45–50 keV.

4.2. Particle-rotor analysis

It has recently been shown [5, 6] that the many-BCS-quasiparticle plus rotor Hamiltonian within a $(i_{13/2})^2$ valence space can be adjusted to give an accurate description of the energies along the g.s. and S-bands of ^{164}Er and ^{166}Yb . If the energies are correct it is expected that the calculation also accounts for branching ratios, and in particular the observed differences between the two nuclei in this respect. For ^{166}Yb the adjustable parameters [5] ($\theta_0 = 35.463 \text{ MeV}^{-1}$, $C = 0.0039308 \text{ MeV}^3$, $\lambda = 0.0545 \text{ MeV}$ above $\epsilon_{5/2}$ and $\Delta = 0.669952 \text{ MeV}$) were fitted in [5] to the yrast levels of spin $I = 0-20$, so the energies of all non-yrast levels, and, furthermore, the branching ratios, can be regarded as predictions of the model. A calculated branching of the yrast cascade at $I = 16$ has been reported earlier [7].

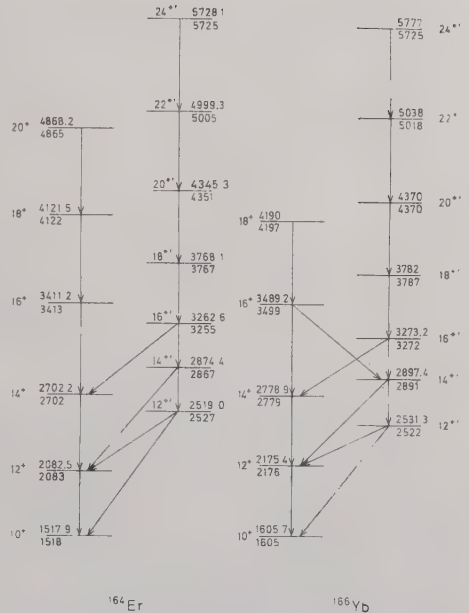


Fig. 4. Comparison of the theoretical and experimental level energies for the g.s. and S-bands of ^{164}Er and ^{166}Yb . The calculated energies are shown below the experimental values.

A comparison between results of the model calculations and experiments is given for the two nuclei in Fig. 4 and Table II. The energies of the non-yrast levels in ^{166}Yb are of course not quite as well reproduced as in ^{164}Er , where levels from the high-spin continuation of the g.s.-band and the low-spin continuation of the S-band were included in the parameter fitting procedure. Nevertheless, the calculation is sufficiently accurate to describe the branching of the electromagnetic decay, cf. Table III. The transitions following the unperturbed bands through the crossing are indeed significantly stronger for ^{166}Yb than for ^{164}Er . Thus the transition from 16^+ to 14^+ has been seen in the ^{166}Yb case but not in ^{164}Er . A decay branch from the 12^+ level to the 12^+ level as well as to the 10^+ level is measured in ^{166}Yb . The 12^+ to 12^+ transition is of particular interest because, according to the calculation, it is an almost pure M1 from the S-band to the g.s.-band. The parameters employed here for calculating the electromagnetic transition rates are $Q = 7b$, $e^{\text{eff}} = e$, $g_s^{\text{eff}} = 0.6g_s^{\text{free}}$, $g_l = 0$ and $g_R = Z/A$. A complication which should be noted is that the observed 12^+ level comes 9 keV above the calculated one, and just as in ^{164}Er , this may indicate an admixture of the 12^+ level from the gamma band [8].

4.3. Cranking model analysis

The alignment plots [9] for the various bands are shown in Fig. 5. The g.s. and the other bands except the S-band, are fitted with the parameters [9] $J_0 = 29 \text{ MeV}^{-1} \hbar^2$ and $J_1 = 136 \text{ MeV}^{-3} \hbar^4$. The corresponding parameters for the S-band have been adjusted to give a constant value of i_x above the backbend

Table II. Comparison of the theoretical and experimental level energies for the g.s. and S-bands of ^{164}Er and ^{166}Yb . The calculated energies are shown in brackets alongside the experimental values.

^{164}Er		^{166}Yb	
g.s.b.	S-band	g.s.b.	S-band
0 ⁺	0 (0)	0 (0)	
2 ⁺	91.3 (91.5)	102.2 (101.9)	
4 ⁺	299.4 (299.9)	330.3 (330.1)	
6 ⁺	614.3 (615.1)	667.8 (667.8)	
8 ⁺	1024.5 (1025.0)	1098.0 (1097.8)	
10 ⁺	1517.9 (1518.0)	1605.7 (1605.3)	
12 ⁺	2082.5 (2082.7)	2175.4 (2176.4)	2531.3 (2522.1)
14 ⁺	2702.2 (2702.4)	2778.9 (2779.3)	2897.4 (2890.5)
16 ⁺	3411.2 (3413.0)	3489.2 (3499.1)	3273.2 (3271.9)
18 ⁺	4121.5 (4122.2)	4190 (4196.6)	3782 (3786.6)
20 ⁺	4868.2 (4865.5)		4370 (4370.0)
22 ⁺			5038 (5018.0)
24 ⁺			5777 (5725.0)

and are $J_0 = 33.5 \text{ MeV}^{-1}\hbar^2$ and $J_1 = 62.5 \text{ MeV}^{-3}\hbar^4$. The fact that the same values of the moment of inertia parameters generally do not give constant alignment values both below and above the backbend has been discussed by Bengtsson [10] and is probably due to the changes in the core associated with the backbending effect. The g.s. and S-bands show up with nearly constant alignments after correction for their mutual interaction, which is assumed to be constant and equal to 50 keV. The point corresponding to the $18^+ \rightarrow 16^+$ g.s.b. transition shows unbending, which is due to a crossing with the S'-band in the particle-rotor calculation.

The experimental Routhians are shown in Fig. 6. The S-band Routhian crosses that of the g.s.b. at $\hbar\omega = 0.28 \text{ MeV}$. The odd-spin odd parity band shows regular behaviour only above spin 11. This band and the even-spin negative parity band built on the 6⁺ state at 1865 keV could be the two lowest bands with $\alpha = 1$ and 0 respectively, built on the neutron levels labelled $[642\frac{5}{2}]$ and $[523\frac{3}{2}]$ at zero frequency [9].

The extrapolated experimental Routhians for these bands cross the g.s. band at $\hbar\omega \approx 0.36 \text{ MeV}$. No concrete assignments have been made for the band with the band head at 1835 keV. The spin of the band head is probably 6. If this is the case, then this band could be the other $\alpha = 0$ even-spin negative parity

band based on the same neutron quasiparticle configuration as mentioned above. It may be noted, however, that the lowest identified member of a similar band in $N = 96$ isotope ^{164}Er has been assigned a spin (8) and has been suggested [9] to belong to the neutron configuration $[642\frac{5}{2}][505\frac{1}{2}] K = 8$.

5. Conclusions

Judging by the first few states of the g.s. bands, the nucleus $^{166}\text{Yb}_{96}$ is more appropriately classified as a stable deformed rotational nucleus than the more neutron-deficient rare-earth isotopes. Previously the only high-spin levels known were the yrast levels up to spin 20 [11]. In the present work six bands are identified, up to spin 24 on the yrast line and up to 23 in one of the side bands, thereby extending the systematics of high-spin band structure into the region of well-deformed nuclei. Many of the states were also populated and assigned similar spins and parities in a parallel study of the $^{162}\text{Dy}(\text{C}^{12}, 5n)^{166}\text{Yb}$ reaction at Brookhaven [12]. The positive-parity bands are presumably aligned neutron $(i_{1/2})^2$ configurations and the negative-parity

Table III. Comparison of the theoretical and experimental $B(E2)$ and $B(M1)$ ratios for g.s. and S-bands of ^{164}Er and ^{166}Yb

	^{166}Yb		^{164}Er	
	th.	exp.	th.	exp.
$B(E2, 16^+ \rightarrow 14^+)$	1:1.3	1:0.9	1:0.6	—
$B(E2, 16^+ \rightarrow 14^{++})$	1:1.2	1:0.9	1:0.5	1:0.4
$B(E2, 14^+ \rightarrow 12^+)$	5.2:1	—	35:1	—
$B(E2, 14^+ \rightarrow 12^{++})$	4.4:1	2.1:1	24:1	22:1
$B(M1, 12^{++} \rightarrow 12^+)$	2000:1	1600:1	1200:1	1250:1
$B(E2, 12^{++} \rightarrow 10^+)$				

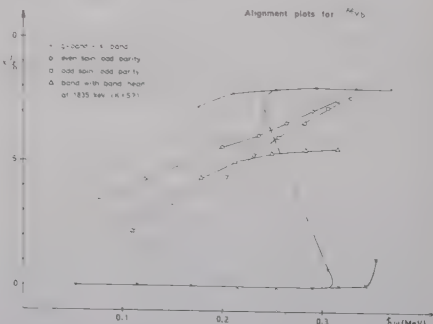


Fig. 5. Plot of the alignment vs. rotational frequency for the various bands in ^{166}Yb . The g.s. and the other bands except the S-band are fitted with the parameters [9] $J_0 = 29 \text{ MeV}^{-1}\hbar^2$ and $J_1 = 136 \text{ MeV}^{-3}\hbar^4$. The corresponding parameters for the S-band have been adjusted to give a constant value of i_x above the backbending and are $J_0 = 33.5 \text{ MeV}^{-1}\hbar^2$ and $J_1 = 62.5 \text{ MeV}^{-3}\hbar^4$.

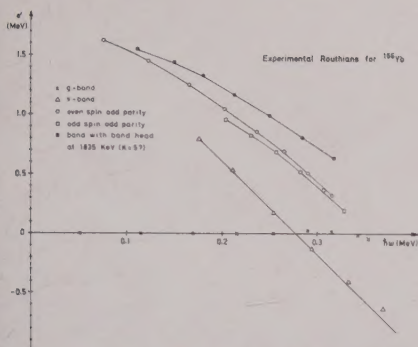


Fig. 6. Experimental Routhians for the various bands in ^{166}Yb .

bands could be neutron $(i_{13/2})(h_{11/2})$ configurations [9]. The VMI parameters, Routhians and values for the aligned angular momentum are extracted from the data. A gamma correlation experiment [13] has also been made recently, which reaches the very high-spin states in the isotopes around ^{166}Yb , and the information obtained in the present work about the detailed spectroscopy up to spins above 20 should be a valuable aid in the interpretation of the results [2, 14].

The crossing between the g.s. and S-bands of ^{166}Yb has a special feature. It is the first known case of a crossing between two interacting bands in deformed rare-earth nuclei where a significant fraction of the cascade intensity leaves the trajectory of the lowest energy in order to follow an unperturbed band characterized by intrinsic structure. The mechanism is a small interaction combined with a band crossing spin in between the even integer values where there are physical states. Heating of the nucleus by this mechanism may occur more frequently for

band crossings at higher spins. A number of interband transitions are observed in the present case at and just below the crossing, which provide more of a test for theory than the data on other backbending rare-earth nuclei. The levels and the M1 and E2 transitions matrix elements obtained from an $(i_{13/2})^2$ plus rotor calculation, made before the experiment and fitted to the energies along the yrast line, turn out to be consistent in detail with the observed energies and intensities.

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References

- Bohr, A. and Mottelson, B. R., Proc. Int. Conf. on Nuclear Structure, Tokyo (1977).
- Delaplanque, M. A., Physica Scripta 23, 000 (1981).
- de Boer, F. W. N., Goudsmit, P. F. A., Koldewijn, P. and Meyer, B. J., Nuclear Physics A225, 317 (1974).
- Bengtsson, R. and Frauendorf, S., Nuclear Physics A314, 28 (1979).
- Almberger, J., Hamamoto, J. and Leander, G., Nuclear Physics A333, 184 (1980).
- Almberger, J., Hamamoto, J. and Leander, G., Physica Scripta (in press).
- Chen, Y. S., Garrett, J. D., Almberger, J. and Leander, G., Physics Letters 94B, 468 (1980).
- Johnson, N. R., Cline, D., Yates, S. W., Stephens, F. S., Riedinger, L. L. and Ronningen, R. H., Phys. Rev. Lett. 40, 151 (1978).
- Bengtsson, R. and Frauendorf, S., Nuclear Physics A327, 139 (1979).
- Bengtsson, R., To be published in J. de Phys.
- Lederer, C. M. and Shirley, V. S., Table of Isotopes, 7th edition, John Wiley & Sons, New York (1978).
- Sunyar, A. W., Private communication.
- Herskind, B., Private communication.
- Leander, G., Chen, Y. S. and Milsson, B. S., Physica Scripta 23, 000 (1981).

